Space Station
Needs, Attributes and Architectural Options Study

Contract NASW-3680

D180-27477-1

Final Report

Volume 1

Executive Summary

April 21, 1983

for

National Aeronautics and Space Administration

Headquarters

Washington, D. C.

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BOEING

FOREWORD

The Space Station Needs, Attributes and Architectural Options Study (Contract NASW-3680) was initiated in August of 1982 and completed in April of 1983. This was one of eight parallel studies conducted by aerospace contractors for NASA Headquarters. The Contracting Officer's Representative and Study Technical Manager was Brian Pritchard. The Boeing study manager was Gordon R. Woodcock.

The study was conducted by Boeing Aerospace Company and its team of subcontractors:

Arthur D. Little, Inc. (ADL)	Materials Processing in Space
Battelle Columbus Laboratories	Materials Processing in Space
ECON, Inc.	Pricing Policies and Economic Benefits
Environmental Research Institute of Michigan (ERIM)	Earth Observation Missions
Hamilton Standard	Environmental Control and Life Support Equipment
Intermetrics, Inc.	Software
Life Systems, Inc. (LSI)	Environmental Control and Life Support Equipment
Microgravity Research Associates (MRA)	Materials Processing in Space
National Behavioral Systems (NBS)	Crew Accommodations and Architectural Influences
RCA Astro-Electronics	Communications Spacecraft
Science Applications, Inc. (SAI)	Space Science

This document is one of seven final report documents:

D180-27477-1	Volume 1, Executive Summary
D180-27477-2	Volume 2, Mission Analysis
D180-27477-3	Volume 3, Requirements
D180-27477-4	Volume 4, Architectural Options, Subsystems, Technology, and Programmatics
D180-27477-5-1	Volume 5-1, National Defense Missions and Space Station Architectural Options Final Report (SECRET)
D180-27477-5-2	Volume 5-2, National Defense Missions and Space Station Architectural Options, Final Briefing (SECRET)
D180-27477-6	Volume 6, Final Briefing

D180-27477-7-1	Volume 7-1, Science and Applications Missions Data Book
D180-27477-7-2	Volume 7-2, Commerical Missions Data Book
D180-27477-7-3	Volume 7-3, Technology Demonstration Missions Data Book
D180-27477-7-4	Volume 7-4, Architectural Options, Technology, and Programmatics Data Book
D180-27477-7-5	Volume 7-5, Mission Analysis Data Book

Note: The volume 7 data books will be distributed to a limited number of requestors.

The study task descriptions and a final report typical cross reference guide are found in Appendix 1.

The Boeing and subcontractor team member are listed in Appendix 2.

Acronyms and abbreviations are listed in Appendix 3.

INTRODUCTION AND BACKGROUND

The concept of a space station arose with the beginnings of serious scientific speculation about orbital flight and space travel. When flight into space was recognized as physically possible about eighty years ago, the idea of a place to live in orbit quickly emerged.

Early thoughts about space stations by Tsiolkovskii and a few others, beginning about the turn of the century, went virtually unnoticed. In the 1920's, however, space flight speculation became popular. Enthusiast organizations arose in the U.S. and Europe and began experimenting with rocket propulsion. Dr. Robert Hutchins Goddard, working mainly in isolation, accomplished the first liquid propellant rocket flight in 1926 and by the late 1930's had pioneered nearly all of the basic features of modern liquid rocket propulsion systems.

As the rudiments of early space flight engineering took shape through the labors of these enthusiasts, accompanying scientific speculation dealt mostly with flights to other worlds. Speculation about life on Mars was in vogue. The ferment in technical circles was mirrored in the entertainment media by the antics of Buck Rogers and Flash Gordon. There was little mention of Earth-orbiting space stations.

And then the industrialized world careened into World War II. The German space flight enthusiasts were co-opted by the Wehrmacht and became the Peenemunde engineering team.

Revolutionary technologies emerged from both sides of the great war; their marriage was inevitable. The technical feasibility of space flight was no longer a question. The remaining questions were when, how, and by whom.

The space station idea blossomed afresh in 1953 with Wernher VonBraun's proposals for a large U.S. space station program. This proposal was ambitious: a rotating wheel-shaped station large enough to house dozens of people. It had national security overtones; VonBraun saw it as a means to enforce a "pax Americana".

Although the engineering architecture of VonBraun's space station and its support fleet of giant rockets was presented in teutonic detail, the mission needs and supporting materials were somewhat hazy.

VonBraun's proposal was made in all seriousness. It was not speculation. It would, however, be quite expensive and a few people began to ask "why?"

During World War II, giant strides in the electronics arts had made it possible to imagine an automated satellite, a prospect not foreseen by the visionaries of the twenties and thirties. The need for humans in space, as assumed in the VonBraun proposal, was not entirely obvious. The issue of "man versus robot" was born.

As these matters were debated in public, national plans for space programs were being developed, somewhat shrouded in secrecy. The U.S. program aimed at a limited objective, orbiting a scientific satellite. The Soviet Union forged a multi-faceted program beginning with automated and manned space flight, intending a relentless evolution through space stations and platforms eventually reaching other worlds.

The U.S. viewed space technology as a means to specialized scientific ends. The Soviets saw it as a logical evolution of the socialist ideal, the extension of their ideology not only throughout the world but throughout the universe.

In 1957 through 1961, the Soviets launched not only the first sputnik but the first manned space flight. The U.S. reaction was a technically awesome challenge: to land a man on the moon and return him safely to Earth, within less than ten years. NASA and U.S. industry mobilized towards this end and performed magnificently. We did this job in just over eight years, and carried out a total of six landings. Each Apollo mission accomplished more than its predecessor. American technological superiority was upheld in the eyes of the world. The space flight dream of the 20's and 30's had become reality.

During the Apollo years, far-reaching planning studies by NASA examined the future of space technology and utilization. NASA began inhouse studies of space stations in 1959. NASA funded an engineering study of a space station as early as 1963. Other studies evaluated reusable launch vehicles, lunar bases, manned flights to Venus and Mars, and automated exploration of all of the planets. Some form of space station occurred in most of these scenarios.

In 1968, as the Apollo program was nearing its goal, NASA outlined an "integrated plan" for space development, including a permanent manned base on the moon and manned exploration of Mars. The plan included a standardized vehicle set, including a reusable launch vehicle, as well as a space station in low Earth orbit.

Fiscal realities caused all of this plan to be abandoned except the launch vehicle and the space station. Phase B preliminary design studies of a space shuttle and a space station were begun over twelve years ago. The inexorable fiscal vise then caused NASA to choose between these two projects. NASA chose the former, sensing that routine manned access to space is an essential precursor to permanent presence.

As these events were occurring, NASA utilized remaining assets from the Apollo program to launch and periodically occupy a temporary space staton, the Skylab. Virtually all we in the U.S. know about long-term human operations in space came from this program that flew ten years ago.

Meantime, the Soviet Union, having lost the race to the moon (and having then claimed that they were never in it), proceeded with their own space station program. After a few years of difficulties and one fatal accident, the Soviet Salyut 6 operated successfully for several years, and has now been superseded by Salyut 7. The Soviets have an order of magnitude more manned space flight experience than the U.S. and a growing lead. It will be 1985 before shuttle flight crews accumulate the number of flight days on orbit racked up just by the 210-day Salyut 7 mission in 1982.

NASA renewed space station concept design studies in 1979. These efforts by the Marshall and Johnson centers and their contractors included some mission analysis but emphasized design and operational concepts and issues.

Perceptions of these space stations were much different than the science laboratory concepts of earlier years. Although science was still present, other applications such as transportation operations, construction of large structures and spacecraft, maintenance and repair of satellites, and developing space manufacturing technologies now were seen as the predominant uses.

These studies, together with the initial successes of the space shuttle and the ensuing "what next" questions again raised the twin issues of space station mission needs and the role of humans in space.

To respond to these issues, NASA elected to place with aerospace industry a series of mission analysis studies. These were to concentrate heavily on mission needs as expressed by potential users of a space station. A broad sampling and diversity of information was obtained by issuing a total of eight contracts, and instructing the contractors not to exchange data or results during the course of the studies.

This report presents a summary of the mission analysis results obtained by The Boeing Company.

STUDY OBJECTIVES

The objectives of the study were straightforward:

(1) To identify valid missions for a space station as perceived by potential users;

(2) To set forth quantitative requirements for a space station based on, and traceable to, the users' mission needs;

(3) To characterize and quantify the benefits accruing to the users and to society, should a space station be built and placed in service;

(4) To specifically quantify the <u>benefits</u> of human presence in space and compa[illegible]

these to the costs of supporting permanent human presence in space, as compared to serving the same mission needs through unmanned space platforms and spacecraft, together with the intermittent human presence that accompanies shuttle flight operations.

These results are to be used by NASA as a basis for decision as to whether to press forward with a space station program.

ISSUES ADDRESSED

This executive summary report addresses the following issues:

- o Identification and validation of missions: Who are the users? What are their needs? When will they arise? What are the benefits of a space station?
- o Benefits of manned presence in space: Is manned presence beneficial? What is the human role? Does the need for manned presence justify a space station?
- o Needed attributes and overall architectures: How do user mission needs reflect into specific needs for attributes and architectural features?
- o Requirements imposed on space station: What are the time-phased mission and system requirements?
- o Selection of orbits: Where should we fly?
- o Space station architectural options: Which architectural approaches are attractive? Which ones are not?
- o Technology selection: What technologies should be incorporated into the initial space station? How can we provide for technological advance?
- o Program planning —
  - o Costs and benefits: What is the range of program life cycle costs?
  - o Risk and cost avoidance: How can we control risk and avoid unnecessary cost?

IDENTIFICATION AND VALIDATION OF MISSIONS

Mission needs were developed by a combination of user contacts and literature search as symbolizd by figure 1. The bulk of the effort went into user contacts in order to ensure a fresh, up-to-date, user-oriented view of mission needs.

Our most effective means of obtaining a broad scope of user input was through telephone interviews. We found that our mission investigators could contact a wide range of users and get the essential information from each in a relatively few minutes. Letters, however, often went unanswered. In cases of high interest we undertook visits to specific potential users to gather data in greater depth. In certain areas, such as communications spacecraft and microgravity processing, we found that subcontracts with potential users were essential to developing a thorough understanding of mission utility and benefits.

All user data inputs were compiled on mission data forms and recorded in a computer data file. This provided the source record from which the space station missions were developed.

The mission data forms and related literature data provided a raw mission data set of potential missions traceable to user needs. This raw mission data set exhibited several problems. Firstly, there was significant overlap and duplication among different mission categories. Secondly, although scientific mission inputs were usually clear on utility and purpose, this was not true in some other areas. It was necessary for us to make judgements as to whether each mission had a utility and purpose such that it should be retained.

Thirdly, some of the user mission inputs had little relationship to space station and did not appear to represent valid space station missions. Finally, many of the user needs were stated in terms of objectives or science results instead of instrument or equipment requirements. We found it necessary in those cases to matrix missions versus instruments and equipment to avoid duplication and to identify instrument needs.

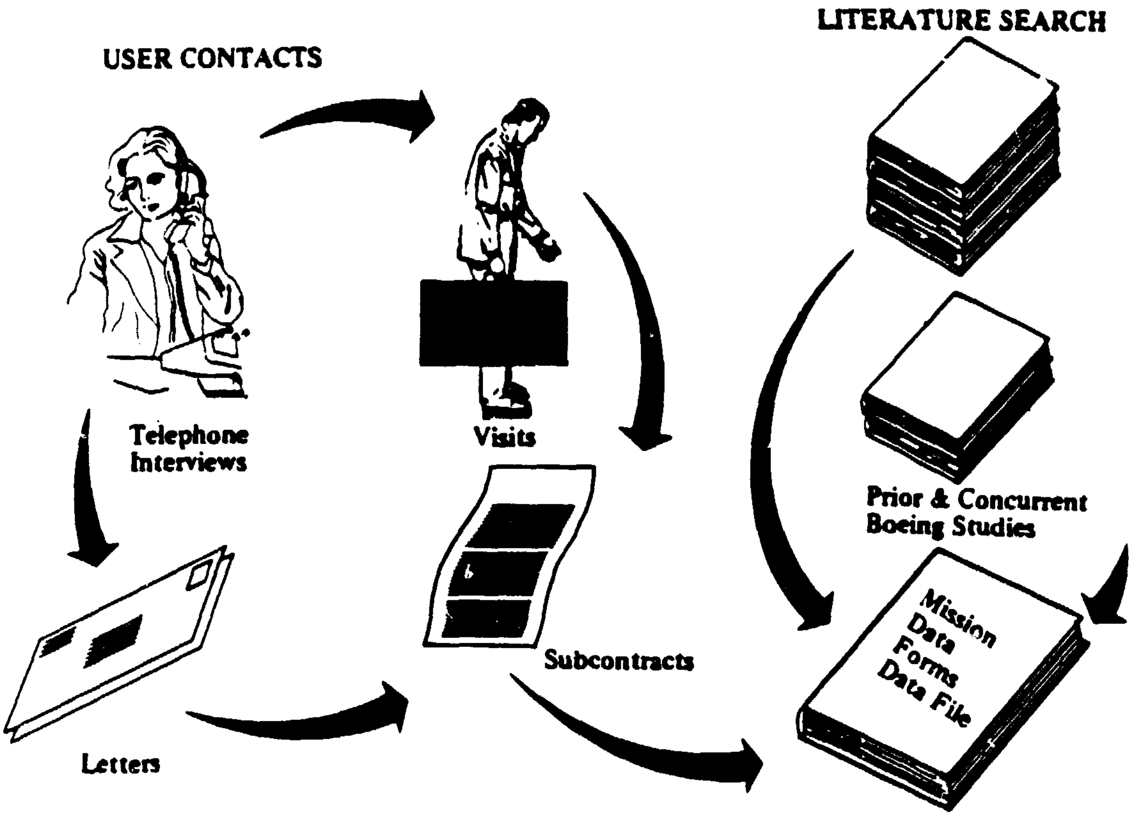

Figure 1. Developing Mission Needs Data

This initial screening provided a set of valid mission needs stated as mission requirements. We then applied additional screening criteria, including judgements as to relative priority and logical sequencing, combined with cost analysis of mission equipment, to initiate a process of disposition and scheduling. This process considered orbital inclination, placement of the mission on a station or on a free flyer, aggregation of individual instruments and experiments into meaningful space station payloads, identification of servicing and support needs and crew involvement. Finally, the missions and payloads were prioritized and scheduled in consonance with reasonable budgetary expectations.

This interactive process, diagrammed in Figure 2, resulted in a space station mission manifest and traffic model. This mission manifest featured aggregation of missions into 46 logical payloads, such as an earth observation pallet including eight instruments, and a life sciences research facility responsive to dozens of individual life sciences missions.

Figure 3 illustrates the final manifest results for the science missions. Shown are orbit inclination, the time period when the mission is active, crew involvement needed to conduct the mission itself or to service the mission or equipment, the disposition as to spacecraft type, and finally servicing means.

Those missions described as carry-ons did not require specific manifesting on space transportation, but did demand space station services.

SCIENCE AND APPLICATIONS MISSIONS

Science and applications missions need placement in high inclination and low inclination orbits, as summarized in figure 4. A high inclination space station would conduct earth observation missions and plasma physics missions that need exposure to the auroral zones. One radiation-oriented life sciences mission was assigned to high inclination. Low inclination missions include materials processing, life sciences, and astrophysics and solar observations.

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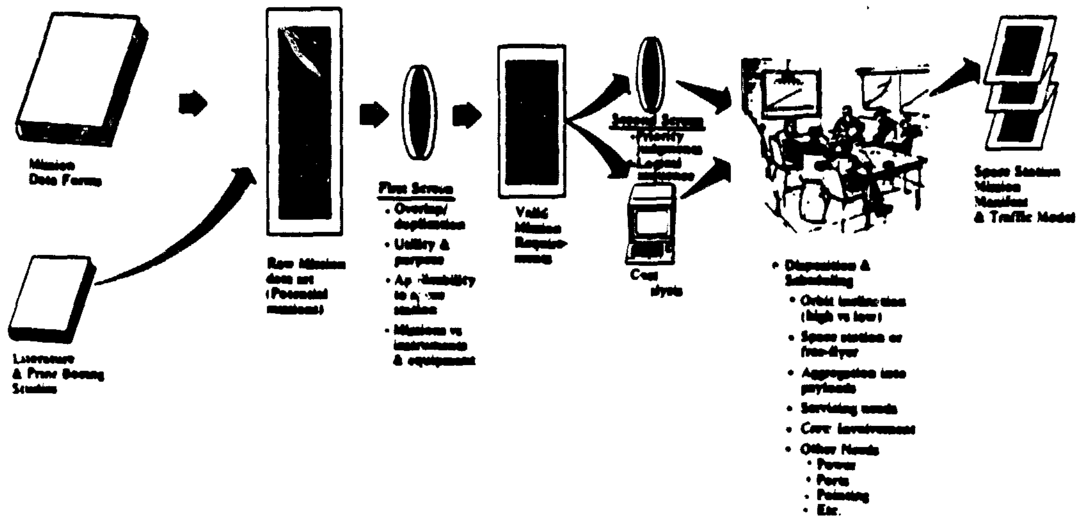


Figure 2. Developing the Space Station Mission Manifest

MISSION	ORBIT (DEG.)	TIMING 90 95 00 05	CREW INVOLVEMENT: MISSION OPS	CREW INVOLVEMENT: SERVICING	PLACEMENT	SERVICING MEANS
EARTH OBSERV PALLET	98		X	X	ON SPACE STA	IVA/EVA
SYNTH APERTURE RADAR	98		X	X	ON SPACE STA	IVA/EVA
LIDAR	98		X	X	ON SPACE STA	IVA/EVA
UPPER ATM	98		X	X	ON SPACE STA	IVA/EVA
SCI SUBSAT	98			X	FREE FLYER	EVA
SPACE PHYS	98			X	ON SPACE STA	IVA/EVA
VLBI/COSMIC RAY	98			X	ON SPACE STA	IVA/EVA
RADIATION BIOL	98		X	X	CARRY-ON	IVA
HUMAN LIFE SCI	29		X	X	CARRY-ON	IVA
SM MAMMALS	29		X	X	CARRY-ON	IVA
PLANT DEV	29		X	X	CARRY-ON	IVA
LIFE SCI RF	29		X	X	DEDIC MODULE	IVA
CELSS MOD	29		X	X	DEDIC MODULE	IVA
ASTROPHYS OBS	29			X	FREE-FLYERS	EVA/TMS
ASTROPHYS PLAT	29			X	FF PLATFORM	EVA/TMS
ASTRO/SOLAR CLUS	29		X	X	ON SPACE STA	IVA/EVA
LARGE RADIOTEL	29			X	FREE-FLYERS	EVA CONSTRUCT EVA/TMS SERV

Figure 3. Science Mission Disposition

Benefits of crew presence include instrument and equipment servicing, and direct involvement in the missions themselves. The principal categories of crew activities are noted on the figures. A major benefit of the space station is in manned servicing of instruments. This enables accumulation of science assets in space over long periods of time instead of using most of the available science and applications funds on instrument replacement, as is true today.

We found that most life sciences, and some materials, astro- and solar physics missions are impractical without crew presence. Crew presence also contributes to earth observation missions through selecting targets of opportunity and coordinating instrument operations.

- **Benefits of crew presence:**
  - **Instrument and equipment servicing (Predominant for Earth observation, Plasma Physics, and Astrophysics)**
  - **Involvement in mission (Predominant in Materials Processing, Life Sciences, and Solar Physics)**
    - **Carry out experiments/act as subjects**
    - **Identify transient events and coordinate instruments**

- **Servicing enables accumulation of instrument assets rather than replacement.**

- **Most Life Sciences, some materials, some astro/solar physics missions impractical without crew presence.**

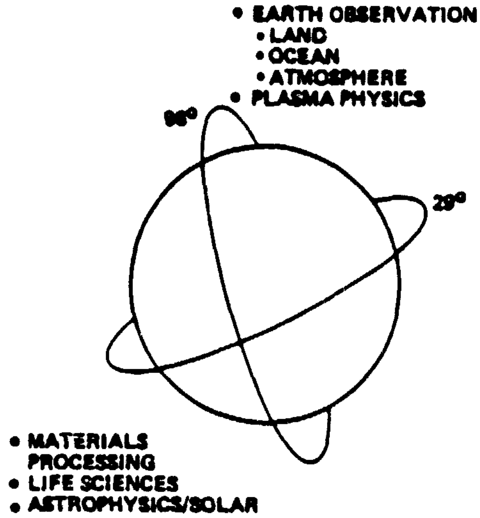


Figure 4. Science & Applications Mission Needs

COMMERCIAL MISSIONS

Materials processing dominates commercial mission needs. We found crew involvement to be essential for research and development as well as for production servicing operations. The role of manned presence is most important in the development of processes to enable rapid experimental progress. The materials processing missions offer high economic value and benefit.

We found that exploratory research can readily be accomplished on shuttle flights. Process development is most appropriate to a laboratory attached to a space station. Fully-developed processes in production may best reside on dedicated platforms. For example, semi-conductor crystal growth needs very high power in the production phase. Accordingly, it was allocated to a separate free-flyer platform to avoid burdening the space station power system with its power demands.

These missions need frequent shuttle flights and were the principal reason for traffic growth in the traffic model.

The space station enables some of these missions and enhances all of them.

Hundreds of different materials processing experiments have been proposed. Many could undoubtedly lead to commercial products. However, at the present state-of-the-art we were able to identify only three that have (1) definable market demands, (2) known processes that offer significant advantages over earth based processing and (3) product values high enough to absorb the high cost of space transportation. These are special semi-conductors, pharmaceuticals, and optical glass fibers. The market projections for these three areas are shown in figure 5 and reach a cumulative market potential on the order of ten billion per year by the year 2000.

Whereas the market for each of these products is speculative and subject to certain risks, it is indicative of the high economic potential of materials processing in space. One or more of these products may fall by the wayside, but it is likely that others will fall in place, especially if a space station provides a materials processing laboratory to permit intensive micro-gravity materials research.

To assess the benefit of a space station in servicing of communication satellites, we felt it was essential to go to a satellite manufacturer for evaluation. Accordingly, we subcontracted to RCA Astro-electronics to investigate the utility of a space station. RCA identified two applications:

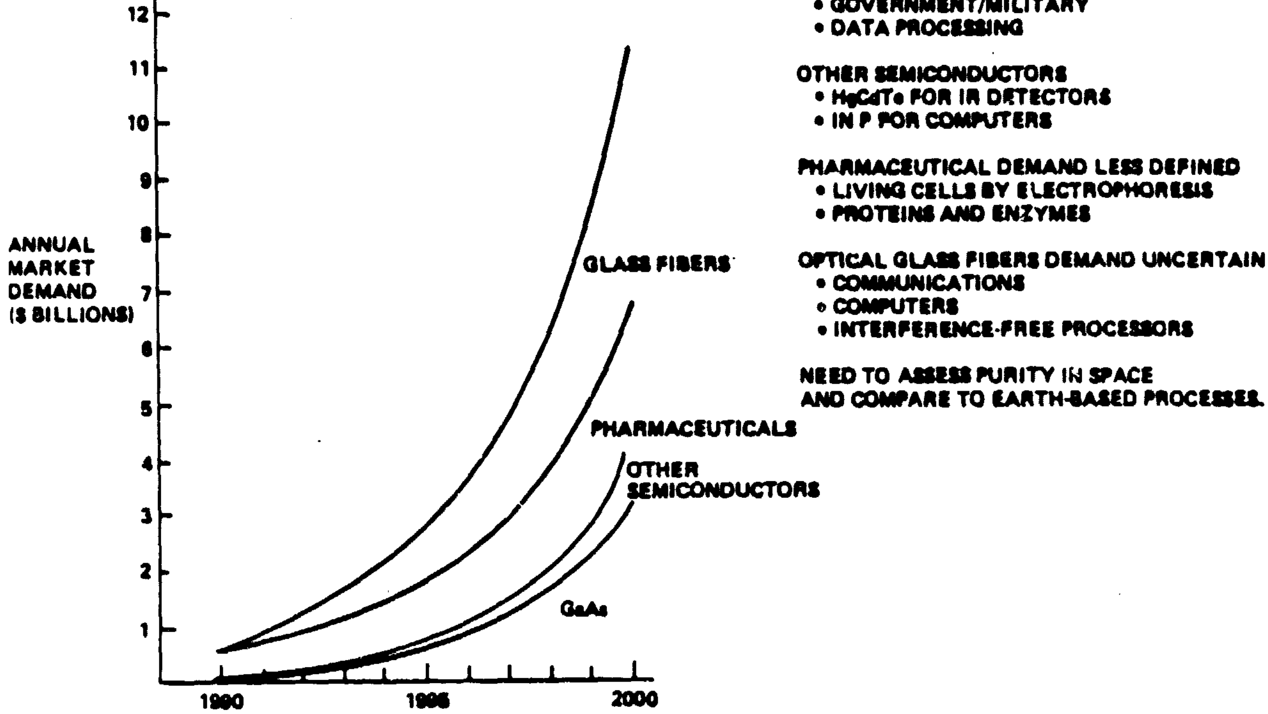


Figure 5. Market Projections for Materials Processed in Space

1. Reconfigurable direct broadcast satellite spares. Present concepts for direct broadcast TV employ one satellite to cover each U.S. time zone. Each of four active satellites will have a beam shape appropriate to its particular time zone. Because of the risk of unplanned outage, "hot" spares must be available in orbit. One spare is required for each pair of time zones since it is possible to include two antenna feeds on each to create two beam shapes. Hot spares in geosynchronous orbit are, of course, using up their propellant and lifetime while waiting to be used in the event of an outage.

   If a space station is available, a single hot spare could be provided there. Upon need for replacement, the proper feed horn could be installed and the satellite quickly launched to the destination orbit. The satellite would include integral propulsion for quick-response launch.

2. Assembly and test of large aperture antenna platforms. RCA identified potential needs for future communications satellites with antennas up to thirty meters in diameter as depicted in the lower right of figure 6. The space station provides the necessary crew participation in the construction process. The alternative is to use STS revisits to satisfy the construction time requirement. This is risky because large antenna systems will have very short orbit lifetimes unless attached to a space station. Although we considered space shuttle revisits for construction in one scenario, we believe the space station is enabling for large antenna construction in low Earth orbit.

TECHNOLOGY DEVELOPMENT MISSIONS

Our original set of technology development missions numbered 76. Principal mission categories included space structures, large optics, flight controls, fluids, robotics, and energy technology as noted in figure 7. The number of missions was reduced to 33 by screening for duplication and overlap and by applying budgetary and scheduling considerations.

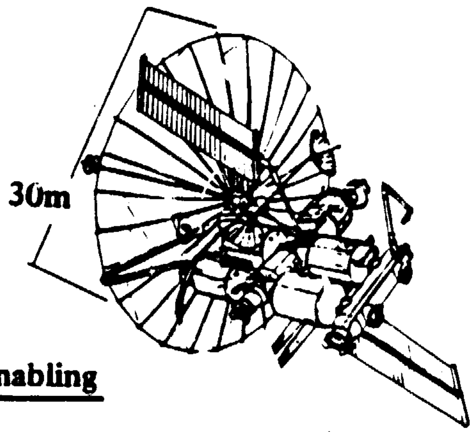
The 33 missions divided into three cate-

Two applications identified by RCA

(1) Reconfigurable direct broadcast satellite spares-space station provides: storage, installation of correct feedhorn, quick-response launch.

(2) Assembly and test of large-aperture platforms space station provides crew involvement in construction—

Alternative is STS revisits for construction time.



Space station is essentially enabling for large antenna missions.

Figure 6. Communications Satellites

- **Original set of 76 candidate missions was cut to 33 by screening and budgetary considerations.**
- **Space structures and optics, flight controls, fluids, robotics, and energy technology identified as important.**
- **Space station is enabling for 43% of these missions.**
  - **Size and handling**
  - **Support equipment needs**
  - **Short life time in orbit unless attached to space station**
  - **Extensive crew involvement, e.g. for construction, calibration and test.**

Model of large antenna

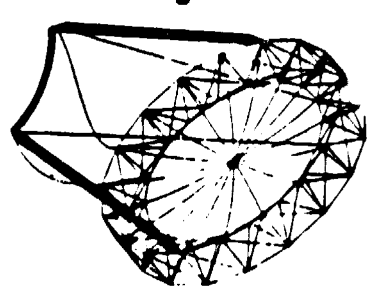


Figure 7. Technology Development Missions

gories roughly equal in number. First were environmental control and life support technology development missions, assigned to the space station technology and development program. These, if they required flight testing, would be manifested on shuttle flights during the space station technology or development programs. The other two categories were those that could be performed without a space station (at greater cost) and those that require a space station. Of the applicable technology development missions identified, about half require a space station.

The space station is enabling for some of

these missions because they require extensive crew involvement, and because some of them have very short orbit lifetimes unless attached to a space station.

In comparing transportation requirements with and without a space station (discussed below), the short-lifetime missions were retained for transportation requirement comparison. But, in actuality, they are not practical without a space station.

We added the robotics device illustrated in figure 8 to the mission set requiring space station because of the need for crew involvement time. A complementary set of these missions included, in addition to spacecraft robotic servicing technology, spacecraft and upper stage servicing and integration, and spacecraft and upper stage maintenance activities. These missions would develop a proper blend of crew use and automation techniques to accomplish effective servicing.

Military mission analyses are reported in a classified report as noted in the foreword. Impact of potential military needs is not addressed in this report.

THE PAYOFF

Although there is no single "smoking gun" mission that by itself clearly justifies a space station, the cumulative payoff of the identified uses is impressive and compelling. Table 1 offers a summary.

Accumulating scientific instruments through servicing will lead to better understanding of the earth's climate, atmosphere, oceans and biosphere. These are issues of enormous long-range practical importance, such as CO_2, climate and sealevel; long-range climatic evolution; is the earth headed for another ice age or could it become once again semi-tropical as in eons past? What is the mechanism of sun/earth coupling? Do sunspots influence climate? Can food production keep up with earth's growing popula-

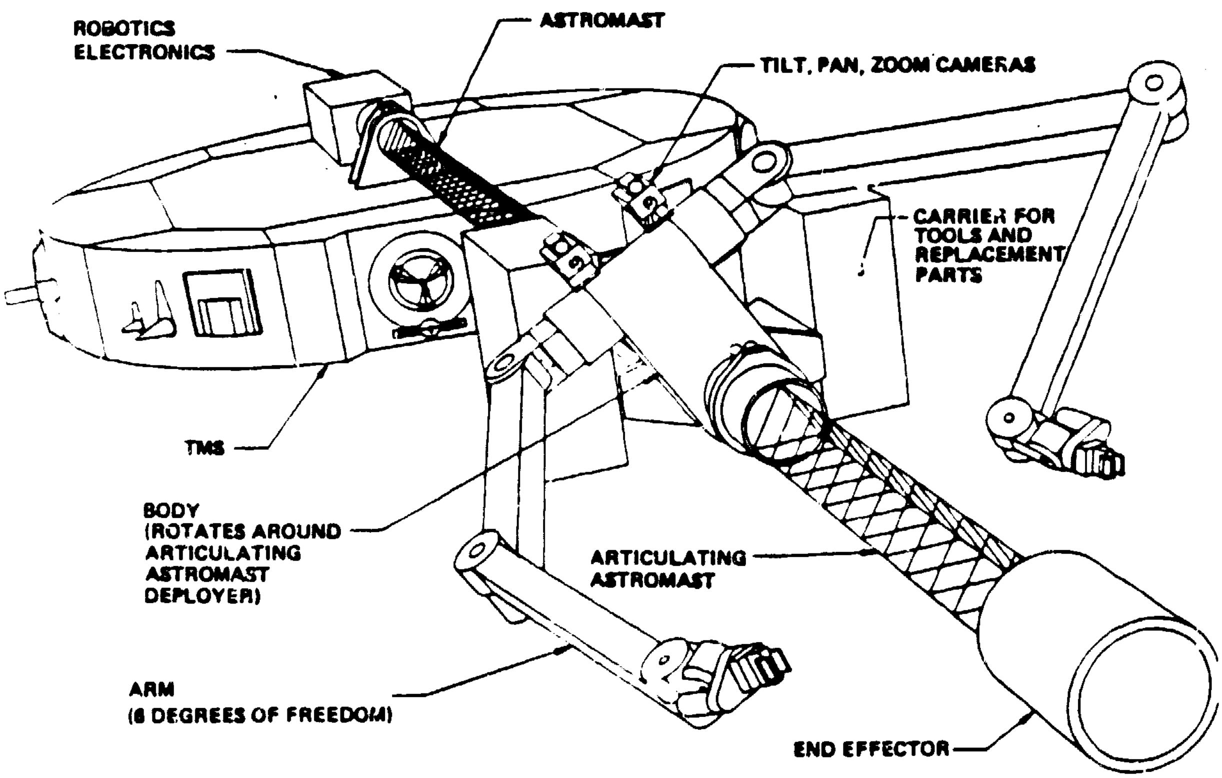


Figure 8. Spacecraft Robotic Servicer

OTHER MISSIONS

Operational missions were a fall-out of the analyses described in the following section.

tion? Are the oceans in danger of being severely damaged by pollution as some people fear?

Table 1. The Payoff

- **Better understanding of Earth's climate, atmosphere, oceans, biosphere.**
  - **CO_2, climate, and sea level** } **Trillion-dollar issues**
  - **Ice age versus semitropical** } **Trillion-dollar issues**
  - **Food production and health of our oceans** } **Trillion-dollar issues**
  - **Sun/earth coupling** } **Trillion-dollar issues**
- **Better understanding of our solar system and universe**
  - **Beginnings and endings**
  - **High energy processes and new phenomena**
- **An added dimension for life sciences and materials research**
- **Cutting edge of high-tech. industrial technology**
  - **Pharmaceuticals: New drugs and biological products**
  - **Semiconductors: Ultrahigh speed and electro-optical computers; next-generation sensors**
  - **"Super" glasses for optical fiber and laser applications**
  - **Large antennas and optics in space**
  - **Robotics**
- **Higher productivity for space transportation**

Servicing and accumulation of science instruments will also permit a better understanding of our solar system and universe. Although not of immediate direct practical application, such knowledge is of enormous cultural value.

Freedom from gravity forces offers an added dimension for life sciences and materials research. The potential payoffs for life science research are much broader than long-term spaceflight. This research could lead to important new understandings of basic biol-gical processes and development, things of great scientific and practical value.

Research has demonstrated the importance of removing gravitational forces for certain materials processes. Economic benefits from materials processing in space are potentially huge. The main use of the ace station is in research and developm of new processes, products and materials. A space station could lead to the industrialization of low earth orbit with unprecedented economic returns.

A space station will enable much more rapid progress at the cutting edge of high technology industry. Preser g U.S. technological supremacy, a very i portant national goal, will be enhanced by permanent human presence in low earth orbit.

Finally, a space station offers higher productivity for space transportation.

BENEFITS OF HUMAN PRESENCE IN SPACE

We used a specific analytical procedure to ascertain the benefits of human presence in space. We could find no general high-level methodology and were driven to a detailed enumerative procedure of mission-by-mission, year-by-year analysis.

Determining the mission payload manifesting and space station accommodations needs is a computation intensive process. Accordingly, we used an automated procedure to speed up the effort. This procedure carries out the functions annotated in figure 9, to assess transportation needs as well as space station accommodations needs.

The results of these computations were reviewed and assessed to correct errors, and to generate and evaluate alternative scenarios. We created three scenarios. First was a mission-needs-driven scenario; second was a program-constrained scenario in which missions were deferred to slow the rate of growth of space station needs; and third was a scenario with no space station but with automated platforms, to enable

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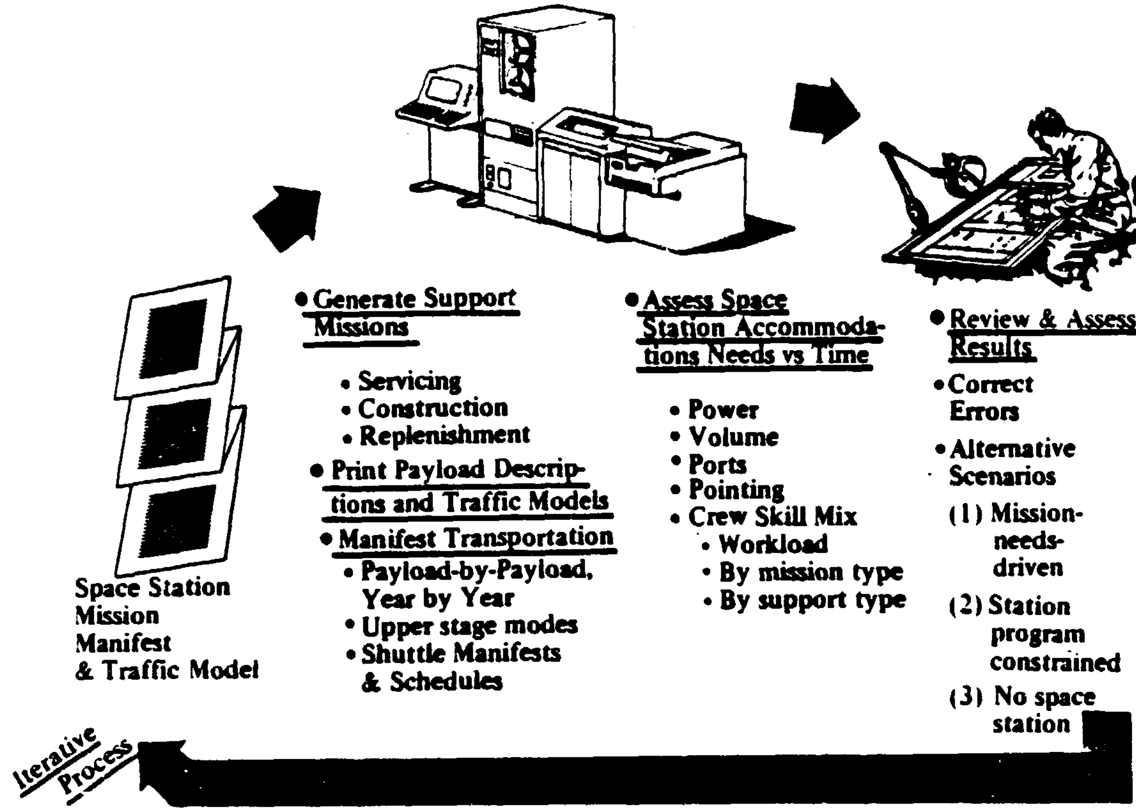

Figure 9. Determining Manifesting & Accommodations Needs

evaluation of the benefits of manned presence.

SHUTTLE TRAFFIC MODEL RESULTS

An important aspect of our benefits analysis was quantifying the influence of the space station on transportation operations. This influence comes about in two ways: improvement in shuttle manifesting efficiency, and reduction of shuttle time on orbit. In this discussion, net results are presented first, followed by explanation of space station/transportation interrelationships.

In order to estimate the quantitative benefit of the space station to space transportation operations, a no-space-station scenario was assembled. In this comparative scenario, crew involvement in mission operations was deleted to avoid unrealistic stressing of the space transportation system. Although certain missions are probably impractical without a space station, e.g., technology development missions and large structures applications missions, they were included in the comparison in order to obtain a valid measure of the benefits of a space station to transportation operations.

DOD shuttle utilization was not included in the traffic model results shown in figure 10.

The availability of the space station reduces the number of shuttle flights required to service the mission model by 10 to 12 flights per year.

Requirements on the shuttle fleet imposed without a space station include additional stay time on orbit as well as additional flights. Consequently, the number of vehicles required to service the mission model increases from roughly six to roughly nine as shown in figure 11. This indicates that the space station offers about 50% improvement in the shuttle fleet productivity.

The fleet size calculations were based on a 35 day turnaround with no operating margin, no time for moving shuttle orbiters between east and west launch sites, and without consideration of DOD traffic.

These mission requirements are heavily driven by the commercial materials processing missions. That activity accounts for most of the growth in flight rate and fleet requirements from the 1990 to post 2000 timeframe.

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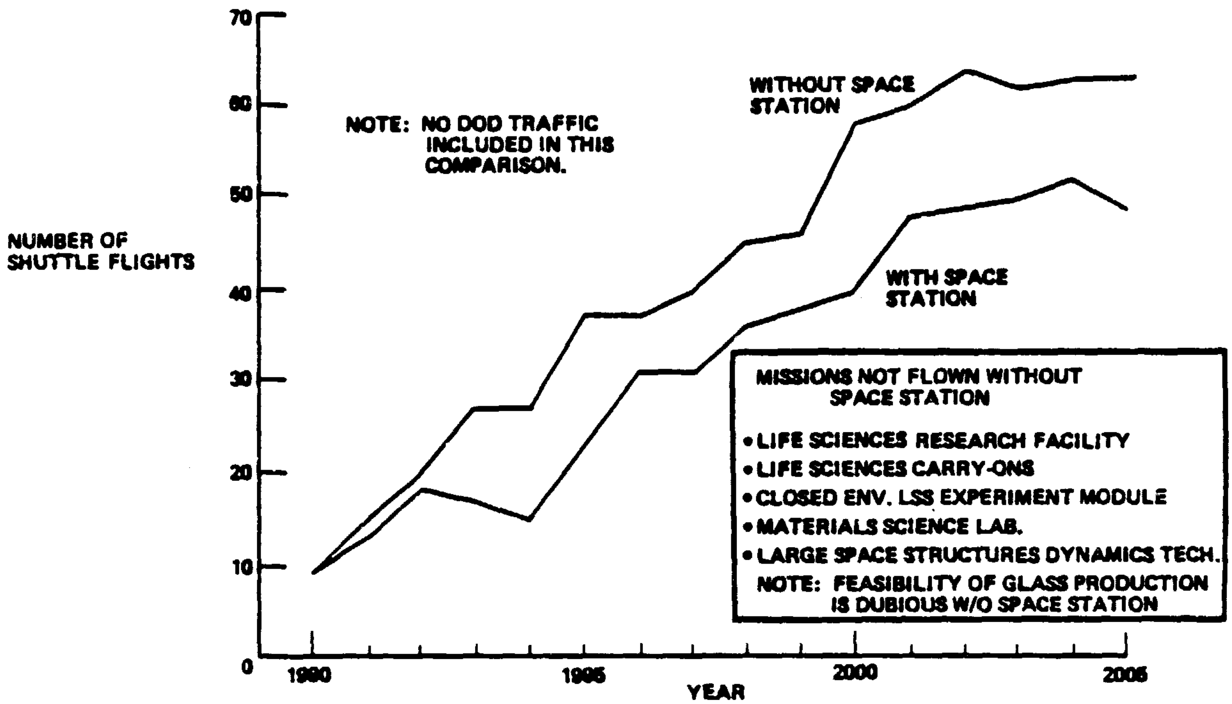


Figure 10. Shuttle Traffic Model Results

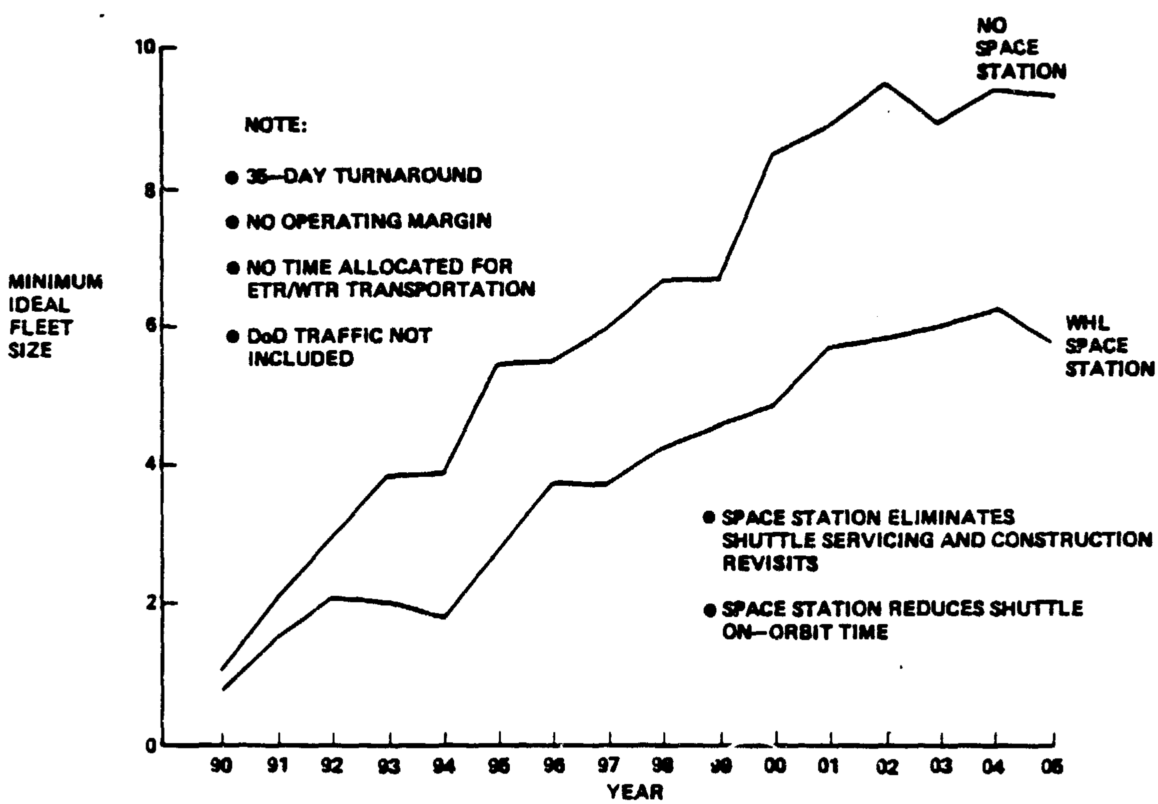


Figure 11. Shuttle Fleet Productivity Improvement

The existence of a space station affects not only shuttle operations, but also upper stage operations.

Assuming that a space station permits space-basing of a manned OTV, the impact of manned GEO operations on launch

requirements is less than might be expected. The result for 12 manned OTV flights to GEO per year is shown in figure 12. The number of additional shuttle flights required to support this level of manned OTV operations ranges from 10 down to roughly 5 or 6 as other traffic increases. This modest impact is an outcome of heavy propellant delivery requirements for the manned OTV operation. Opportunities are presented for mixed manifesting of propellant and payload delivery, thus improving the shuttle mass load factor.

We found TMS to be a very important element of overall space station architecture. If TMS were not available, the formation-flying platforms would all require precision self-propulsion for periodic revisits to the space station.

The presence of a space station relieves the shuttle of flights dedicated to orbital servicing. Manifesting can be more efficient. Less time for the shuttle on orbit is required. These factors add up to roughly a 50% improvement in shuttle fleet productiv-

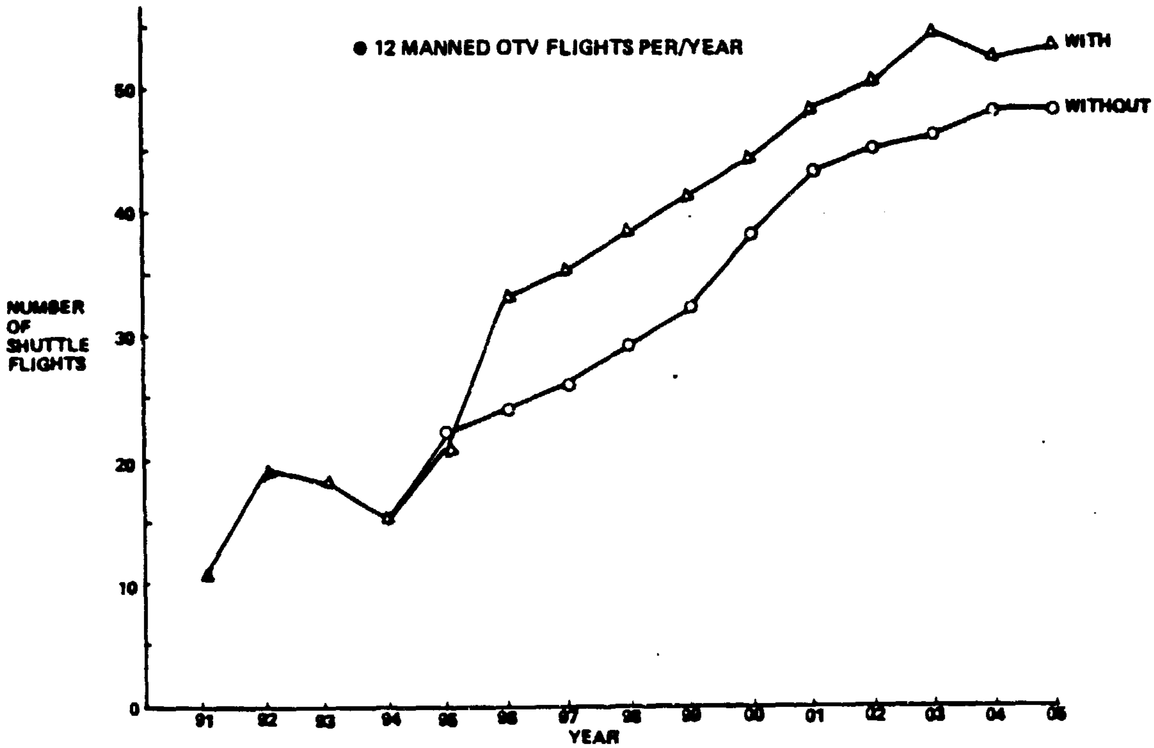


Figure 12. Manned GEO Operations Impact on Transportation

This analysis included shuttle external tank scavenging to improve propellant delivery effectiveness. ET scavenging was included on those missions where payload bay space and shuttle lift capability permitted it.

The level of satellite and commercial platform servicing included in our mission model results in a greater number of TMS operations than OTV flights as shown in figure 13. The TMS operations, of course, require relatively little propellant compared to OTV operations; the typical TMS operation consumes less than 1,000 kilograms of propellant.

ity. A significant contribution to this is the eventual use of space based upper stages to aid in realigning payload mass and center of gravity characteristics through mixed propellant and payload delivery.

The interrelationships between the space station and launch systems are summarized in figure 14.

We did not carry out specific analyses of use of shuttle-derived cargo vehicles in these scenarios. Our results indicate three appreciable benefits. Most significant is shuttle fleet relief and provision of operating mar-

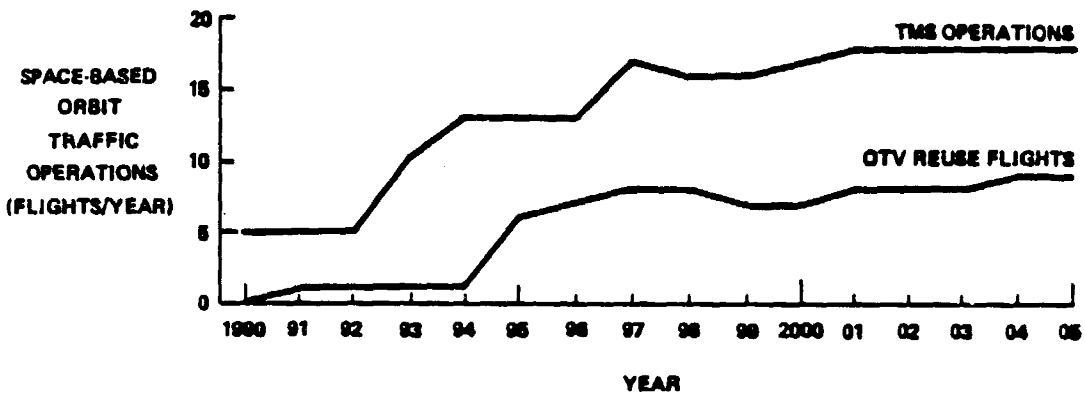
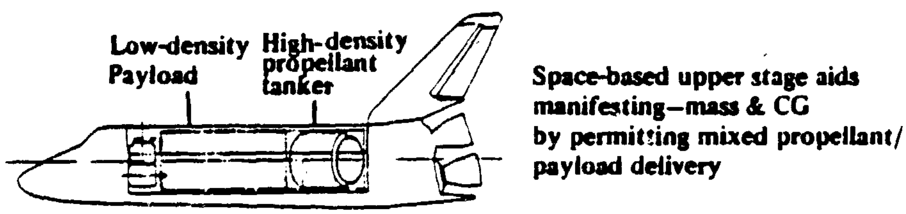


Figure 13. Space Based Traffic Model

- **Shuttle**
  - **Relieved of flights dedicated to orbital servicing**
  - **More efficient manifesting**
  - **Less time on orbit**

  Roughly 50% improvement in fleet productivity



- **Shuttle-Derived Cargo Vehicle**
  - **Fleet relief and operating margin**
  - **Propellant and oversize payload delivery**
  - **No specific heavy-lift requirement identified.**

Figure 14. Space Station/Transportation Interrelationships

gin. Many of the payloads delivered to the space station could be delivered by an unmanned launch vehicle with TMS operations to secure the payload and bring it to the space station. In scenarios with a high level of OTV or manned OTV activity, benefits would accrue from using the shuttle derived vehicle for propellant delivery.

We did not identify oversize payloads, but anticipate that the future will lead to at least a few.

We did not identify specific heavy lift requirements that would place a firm requirement on lift capability greater than that of the shuttle. The shuttle-derived cargo vehicle should be sized to maximize fleet relief, operating margins, and cost-effectiveness.

There are several existing, planned, and contemplated upper stages for space transportation operations. These are summarized in table 2. Typical applications are noted and potential space station utility is described. A checkmark signifies likely benefit, and a bullet signifies dubious or uncertain benefit.

It is important to recognize the potential benefit of assembly to alleviate shuttle CG problems. If several small upper stages such as PAMs and SSUSs with their associated

Table 2. Space Station/Transportation Interrelationships(Upper Stages)

Upper Stage	Typical Applications	Potential Space Station Application
PAMs and SSUSs	Geo transfer payload delivery	√ Holding for longitude drift √ Assembly to help shuttle CG
IUS	Geo payload delivery	• On-orbit storage?
CENTAUR	Geo/planetary payload delivery	• Payload deploy or assembly?
TOS	Geo transfer payload delivery	√ Holding for longitude drift √ Assembly to help shuttle CG
Reusable TMS	Free-flyer science subsatellite Satellite delivery Satellite servicing-manned or unmanned Low-thrust Geo transfer delivery	√ Other leg of mission √ TMS control/basing √ TMS/servicing operations base √ Spacecraft deploy/assembly/checkout
Reusable Ground-based OTV	Geo transfer or GEO delivery	√ Hold for shuttle retrieval √ Spacecraft deploy/assemble/checkout
Reusable space-based OTV	Geo transfer or Geo delivery Manned Geo Access	√ Space Basing: Propellant storage and transfer OTV maintenance Crew cab maintenance ET scavenged propellant storage

payloads are loaded in the shuttle payload bay, a CG problem exists. However, if the relatively dense propulsion stages are grouped in the back of the payload bay and the less dense payloads in the front, the CG situation is improved.

The importance of the TMS to the servicing aspects of space station operations, as well as other functions is evident.

We foresee eventual evolution to a reusable space-based OTV, with the space station providing the services indicated.

A way to summarize the benefits is the following:

One can compare the cost of supporting a mission model with a space station and with automated platforms where additional burdens are placed on space transportation.

The cost of crew workdays on orbit varies widely depending on the circumstances under which the workdays are provided. If crew time can be provided simply by keeping the space shuttle on orbit after it has delivered a payload, the cost is relatively low, that of retaining the shuttle on orbit at roughly a million dollars per day. If additional shuttle flights must be scheduled simply to provide additional crewtime on orbit then the crewtime cost must amortize the cost of shuttle launch and becomes at least ten times as expensive.

Comparing to a space station, we found that a minimum space station program would provide accommodations for approximately 5 crew. One crewmember would be (on the average) involved in operating the space station and not available as useful workforce. This minimum space station would cost between 800 million and a billion dollars a year to support, including a 5 year amortization of initial costs, shuttle transportation costs to service the space station plus mission control costs. These costs are discussed in more detail later in the document.

The space station cost is essentially fixed no matter how small the actual requirements for space crew worktime. For minimal crew on-orbit needs, the space transportation system is the less expensive solution. However, if the time required on orbit exceeds a certain amount relative to the number of available shuttle flights per year, a space station becomes the less expensive solution. Our current mission model crew needs with and without space station are cross plotted on the shuttle cost characteristic curves in figure 15. If a space station is available, much crew worktime on orbit is invested in

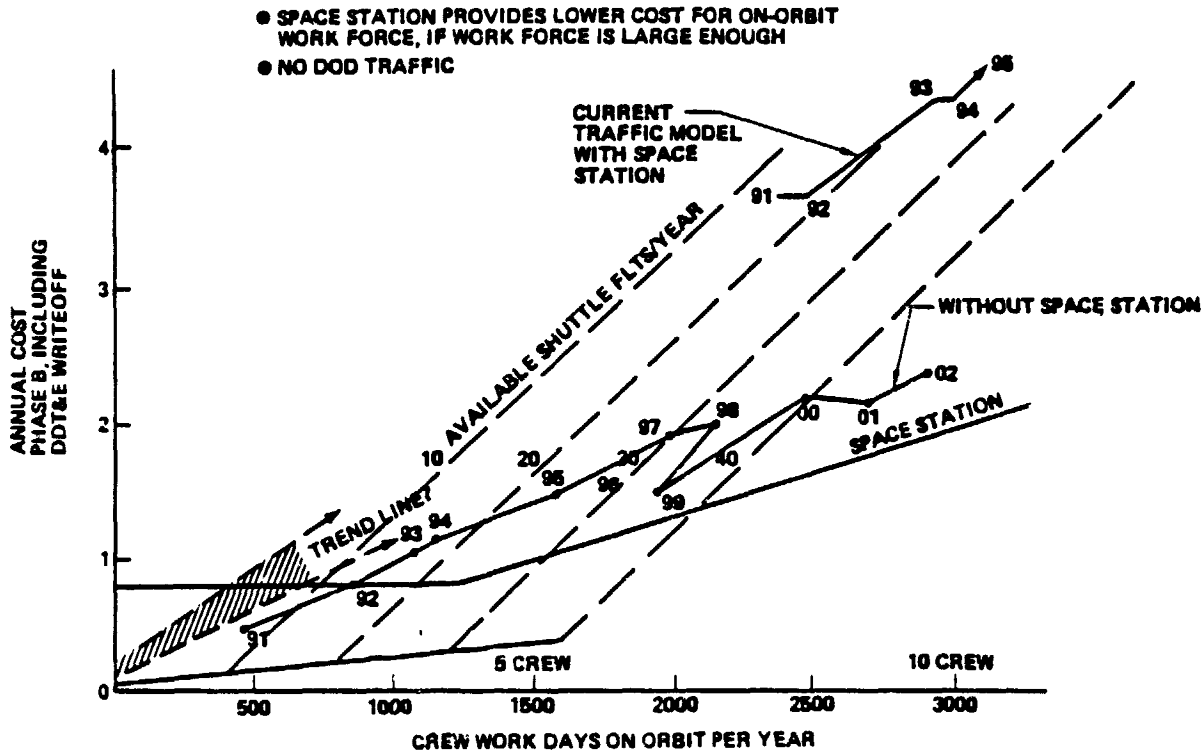


Figure 15. Space Station Economic Benefits

mission experiments and mission operations. Shuttle manifesting is relatively efficient and fewer flights are required. The second curve shown is the crew worktime on orbit without the space station. Shuttle flights for this mission model were counted only when they were not scheduled purely to provide additional crewtime on orbit. In either case, the crewtime versus shuttle flight requirement characteristic curve is in the region where the space station is the cost-effective solution.

The final remaining issue is that of estimating crew needs. The crew demand results used to obtain the above results were derived by making crew task assignments to each payload and mission on an individual basis. The criteria are summarized in table 3. Crew involvement in mission conduct was assigned only if stated as needed by the mission user or mission investigator. Payload and mission servicing were normally assigned crew involvement as necessary in view of the fact that most such servicing will be unscheduled maintenance. Similar factors are true in the construction, checkout, and test of large space structures. Each construction job will be different than its predecessors.

Upper stage turnaround and materials processing development require specific human skills not expected to be available through automation or robotics in the timeframe of interest.

Strong dependence on automation for routine tasks and functions in space station housekeeping was assumed in order to free up crewtime for useful tasks that could not be automated.

As a cross-check, we prepared a forecast of robotics and machine intelligence capabilities in the mid 1990's to judge the validity of the criteria used to assign crew tasks to missions and payloads. It is presented in table 4. We concluded that the task assignment criteria were valid. The uses of the crew assumed in this study will not be practical for robotics or automation in the timeframe of interest.

To recap and summarize the benefits of manned presence: new functions and missions not practical to automate and functions that will improve productivity of utilization of space in the future. Table 5 lists the principal functions, benefits and certain related issues.

Table 3. Why Man? Criteria for Assigning Crew Tasks

PRINCIPAL TASKS	RANGE OF MANDAYS/ TASK	USER PREFERENCE	IMPRACTICAL TO AUTOMATE	
			NO LEAD TIME	TASK REQUIRES HUMAN VISION, JUDGMENT, OR MANIPULATIVE SKILLS
CARGO OFFLOAD	1 – 2			X
SCIENCE MISSION INVOLVEMENT *	5 – 365	X		INTERACTIVE RESEARCH
PAYLOAD/MISSION SERVICING *	1 – 80	X	UNSCHEDULED MAINTENANCE	X
CONSTRUCTION OF LARGE SPACE STRUCTURES PAYLOAD DEPLOY ASSIST	1 – 300		TROUBLESHOOTING	TEST AND CHECKOUT
UPPER STAGE TURNAROUND	5 – 80			X
MATERIALS PROCESSING DEVELOPMENT	90 – 365			INTERACTIVE RESEARCH

* AUTOMATION ASSUMED FOR ROUTINE TASKS AND FUNCTIONS

Table 4. Robotics and Machine Intelligence Evaluation

	Now	Mid-1990's Projection
Natural Language Understanding	Voice word recognition for program control and data entry Limited "recognition" of simple sentence meaning from keyboard input	English programming and data entry with predefined vocabulary and subject matter Some Q&A capability to ensure correct interpretation No ability to deal with unexpected
Dexterity	Simple graspers with tactile feedback Reasonable analogs of human arm Very "weak" for their mass; slow	Reasonable analogs of human hands & arms Improvements in strength and speed but still far inferior to human
Mobility	Experimental–in practical applications, work is brought to machine	Practical in structured environment; e.g., flat factory floor with negotiable obstructions
Eye-Hand Coordination	Recognition and pick-up of isolated geometric objects	Recognition and manipulation of practical objects; e.g., mahine and electronics parts Doubtful ability to carry out complex tasks such as installing a connector
Creative Thinking and Judgment	No capability	Doubtful. Requires conceptual breakthrough followed by extensive R&D

CONCLUSION: The tasks we have assigned to crew are not practical for robotics/automation in the time frame of interest.

Table 5. Benefits of Manned Presence

Function	Benefit	Related Issues
Maintenance and Repair	• Reduced equipment cost • Enhanced availability and life	• Capturing cost savings potentials
Real-time mission involvement	• Reacting to unexpected or transient events • Discovery, insight, & understanding	• Designing mission and instruments to take advantage
Lab operations	• Difficult or impossible to automate • Research progress not paced by shuttle reflight schedule	• Lab equipment at space station • Crew skills
Construction, Assembly, Test Checkout, Modification of large systems	• Difficult or impossible to automate • Simplify designs compared to complex deployment • Stiffen structures • Final test and correction in space	• Role of EVA • Design to capture benefits • Low-thrust transfer to final destination

NEEDED ATTRIBUTES AND OVERALL ARCHITECTURES

Our automated analysis procedure summed the crew needs by mission type and by function. For low inclination missions, the principal crew involvement need exists for servicing and conduct of commercial missions. The crew use in science and applications was primarily for mission involvement, primarily for life sciences missions. Operations involvement included shuttle and space transportation servicing.

Crew involvement by function was predominantly servicing, and secondarily mission operations or transportation operations depending on the timeframe of interest. The construction activity was the least of the various crew needs identified.

The results are shown in figure 16. At about 312 mandays per year, low inclination crew needs grow to more than 20 people.

Figure 17 presents a summary of the same results for the high inclination mission. Again servicing predominated as a mission involvement. The high inclination crew needs in total man days per year are approximately 1/5 of those at the low inclination.

Table 6 summarizes the new insights to needed space station attributes needs gained from the present study.

The magnitude of latent commercial interest in materials processing was surprising to us. This interest is presently deterred by perceived uncertainties and risk, and perception of many years' further research required before major payoffs. It is likely, however, that an initial commercial marketing success for a space-produced material will very quickly transform much of this latent interest into active interest.

Potential benefits for a space station to large commercial communications satellite were identified and verified by RCA.

The significance of servicing cost benefits for science is in providing the opportunity to accumulate rather than simply replace space science assets, offering improvement in space science productivity.

The benefits of a small high inclination space station for earth observation missions and the importance of reaching higher altitudes for a low inclination space station to service astrophysics missions were both new findings. Also, it now appears practical to achieve the higher altitudes by direct insertion space shuttle flights.

We were able to quantify needs for tools, equipment and laboratories to realize the benefits of manned presence and identify three distinct laboratory module functions.

Finally, we accomplished the initial specific quantification of benefits of manned presence reported above, something not accom-

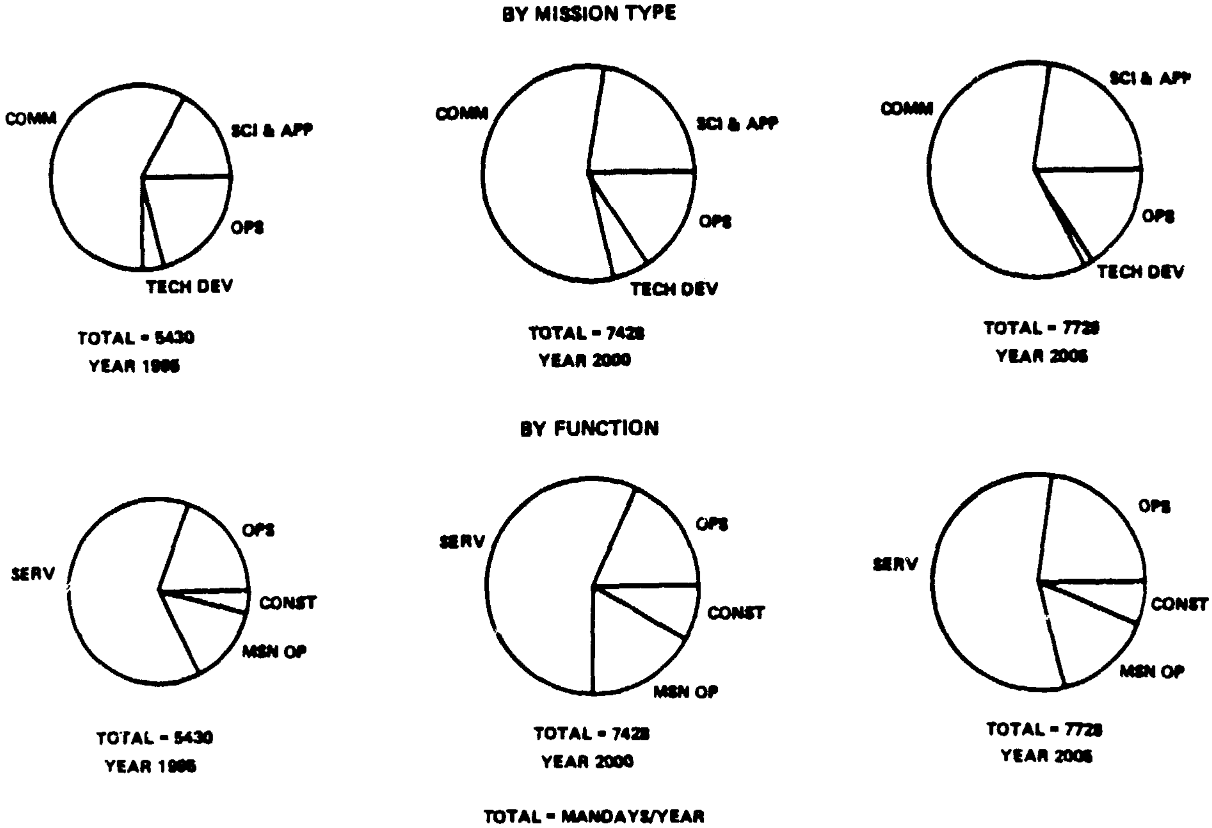


Figure 16. Crew Needs-Low Inclination

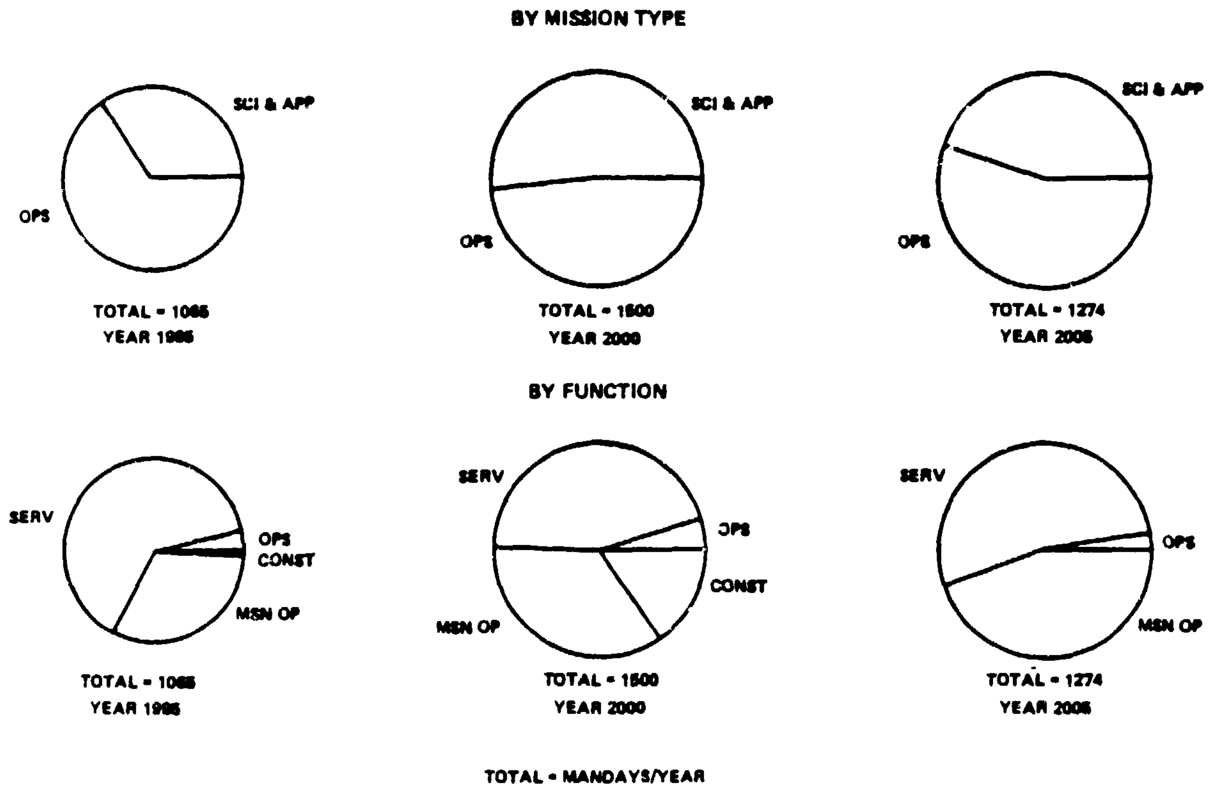


Figure 17. Crew Needs-High Inclination

Table 6. New Insights to Space Station Missions Needs

- **Magnitude of latent commercial interest in materials processing—deterred by uncertainty of access and timing.**
- **Acceptance of benefit of space station to large commercial satellites.**
- **Significance of servicing cost-benefits for science—accumulation rather than replacement of assets.**
- **Importance of high-inclination missions for earth observation**
- **Importance of higher altitudes (500 km versus 370 km) for astrophysics missions.**
  - **Accessible by direct injection.**
- **Importance of tools and equipment to realize benefits of manned presence.**
- **Need for three distinct lab module functions.**
  - **Science operations**
  - **Vivarium**
  - **Diagnostics laboratory**
- **Magnitude of electrical power demand**
- **Initial quantification of benefits of manned presence.**

plished in earlier studies.

Specific needs for space station attributes and architectural characteristics are further elaborated in table 7.

REQUIREMENTS IMPOSED ON SPACE STATION

Mission needs results indicated that we should have both low inclination and high

Table 7. Needs for Attributes and Architecture Characteristics

Need	Source or Rationale
Fly in low inclination low earth orbit	Operations missions; servicing astrophysical observatories.
Fly in high inclination low earth orbit	Scientific and national security missions
Fly either earth-oriented or inertial	Science missions
General purpose lab plus returnable lab	Science missions
Formation fly with free-flyers	Science and commercial missions
Generous workshop and warehouse space	Need to minimize transportation charges for diverse science missions
Mobile crane or RMS	Operations and construction missions
Hangars	Operations and national security missions
Multiple berthing ports	Mission diversity
Securable control room	Accommodation of classified missions
Autonomy	National security missions
Minimum resupply	National security missions
Safe haven and redundancy	Crew safety
Separate work and free-time areas	Crew well-being
Adequate electric power	Aggregated user requirements

inclination capability. The high inclination missions use the crew mainly for instrument repair and secondly for mission operations. The space station serves primarily as an instrument platform and needs a crew of four.

Low inclination missions were much more diverse requiring a variety of crew involvements as noted in table 8. We observed needs for crews greater than 20 in number in the post 2000 timeframe. Accommodation of this number of people may best be achieved by ultimately having two space stations in low inclinations, one aimed primarily at operational needs and the second aimed at scientific needs.

requirements may be limited by the space station program rather than by the evolution of mission needs.

We did not make specific estimates of the data requirements for space station because we do not believe that the input data were sufficiently valid to set a specific requirement for data handling capability. The appropriate program approach appears to be one of providing as much data handling capability as the state-of-the-art permits, not being driven by aggregated user requirements which could easily be off by an order of magnitude at the present state of knowledge.

Table 8. Mission Influences of Requirements and Architecture

- **Missions are clustered around sun-synch and low inclinations. Architecture needs to accommodate both.**
- **High inclination missions use crew mainly for instrument repair; secondarily as mission operator. Space station is instrument platform. Crew of 4.**
- **Low inclination missions are diverse. Variety of crew involvements. Space station is:**
  - **Instrument platform**
  - **Laboratory**
  - **Operations and servicing base**
  - **Construction facility**
- **Crew size starts at 4 – 6, grows to 20.**
- **Flexible, modular architecture needed to satisfy diversity of needs.**
- **High inclination missions need radiation shielding.**

The high inclination mission is subject to solar flare radiation in the event of a solar flare and the system architecture needs to provide space for a radiation shelter for the high inclination mission.

Figures 18 and 19 summarize the space station mission-imposed requirements for low and high inclination missions for the mission-driven scenario.

A second scenario, space-station-program-limited, deferred some of the missions to reduce the rate of build-up of power and crew support requirements. Thus the accommodation of space station mission

SELECTION OF ORBITS

The projected STS payload lift capability shown in figure 20 was supplied to us by JSC. The use of direct insertion increases the altitude capability at nearly full payload to the range of current interest. (500 kilometers is 270 nautical miles.)

For high-inclination missions, the space station altitude will be limited to about 400 km (216 n. mi.) in order to lift payloads up to about 30,000 lb.

In earlier studies, the space station altitude was limited to 370 kilometers by shuttle

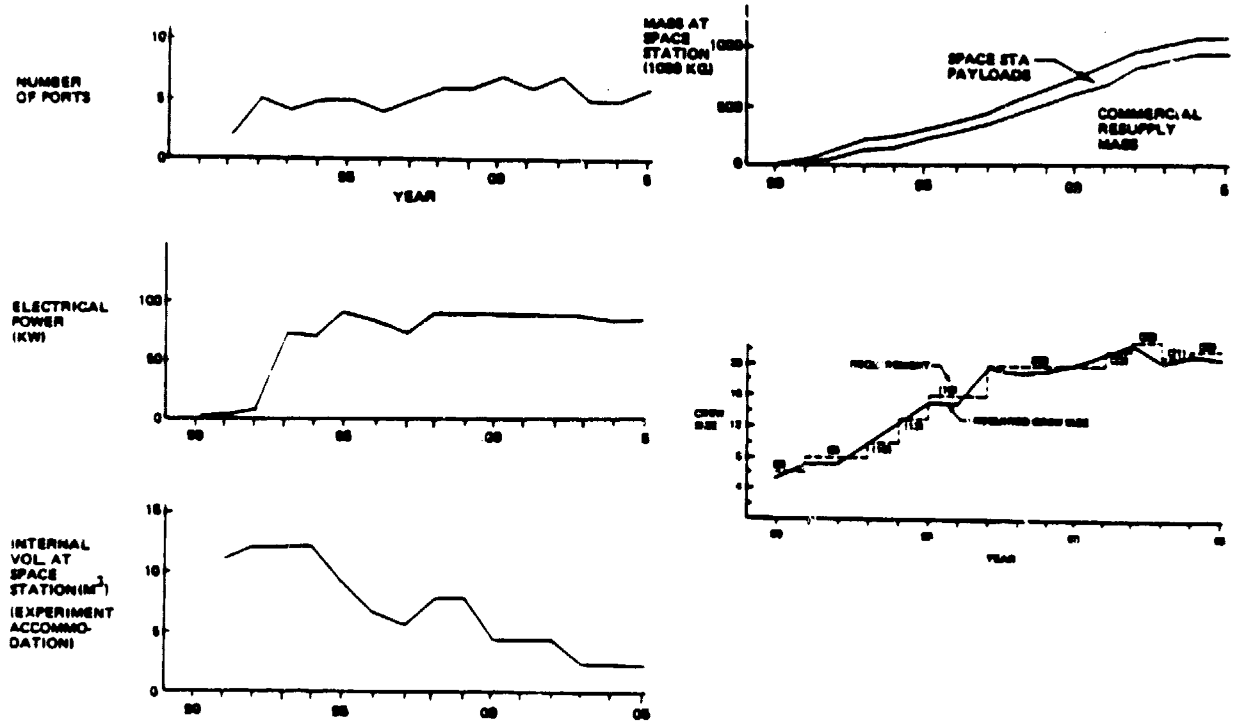


Figure 18. Low Inclination Needs Summary (Scenario A-Mission Driven)

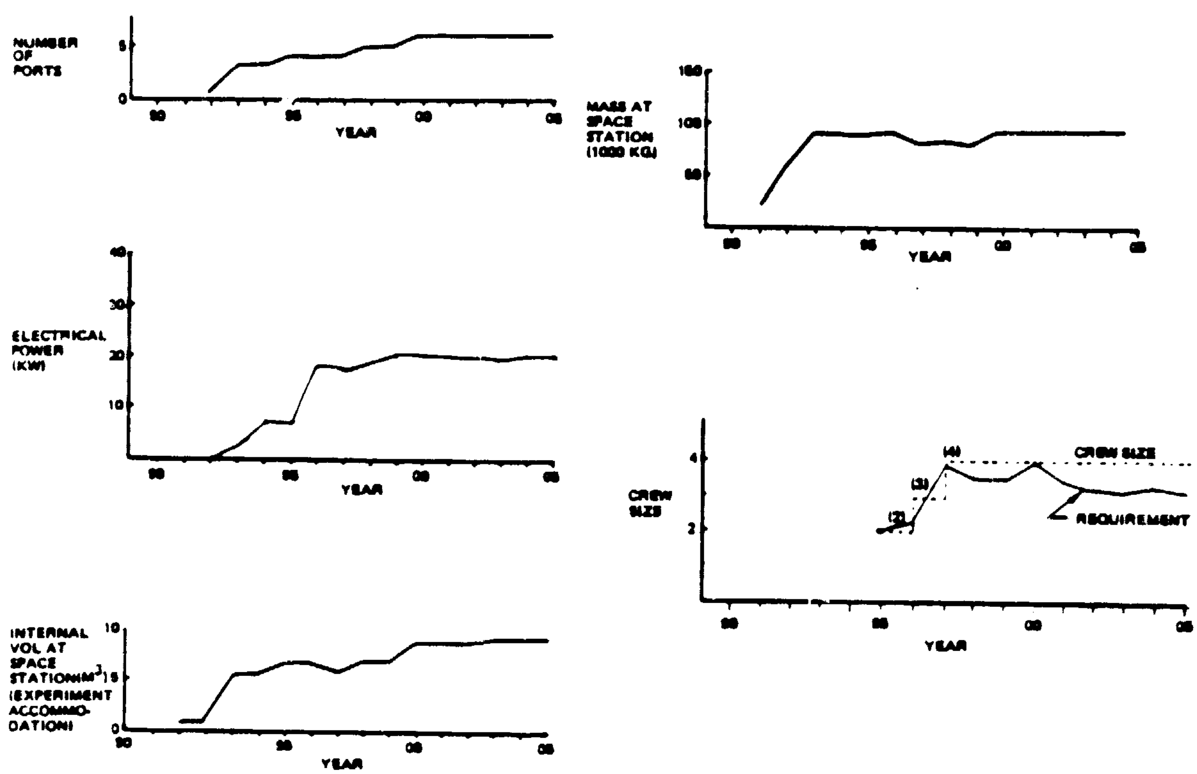


Figure 19. High Inclination Needs Summary (Scenario A-Mission Driven)

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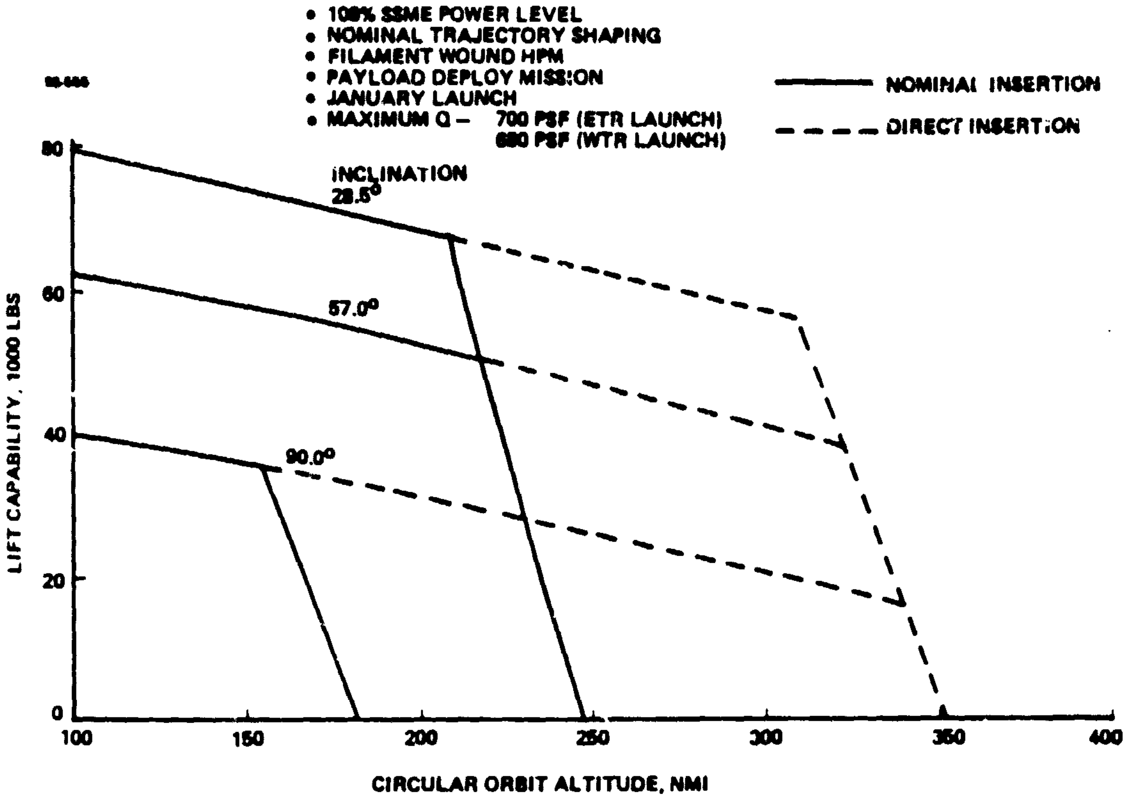


Figure 20. Projected STS Lift Capability

performance considerations. Since that time, NASA investigation of direct injection operations for the space shuttle has offered the capability to operate a low inclination space station at about 500 kilometers altitude and a high inclination station at about 400 kilometers altitude. The higher altitude is very important for servicing of astrophysics missions since the space station and these missions must fly at the same altitude to provide on-demand servicing. The higher altitude reduces drag by roughly an order of magnitude as compared to the lower altitude considered earlier. Consideration of the selection of orbit makeup propulsion technology should be opened for reconsideration, as indicated in table 9.

Figure 21 is modified from the Space Operation Center orbit selection results. It represents an eight-man space station with approximately 50 kilowatts electrical power capability. During the SOC studies the shuttle performance was limited to 370 kilometers without an OMS kit (direct insertion was not considered). The SOC nominal altitude is spotted on the curve.

With direct insertion we can expect to attain about 400 kilometers sun-synchronous and about 500 kilometers for low inclination orbits. This reduces the drag and orbit makeup propellant significantly.

The propellant usage plotted is for monopropellant hydrazine at an ISP of 230 seconds. Usage for other propellant combinations can be adjusted according to specific impulse. For example, the NASA neutral atmosphere at 500 kilometers would require approximately 4 kilograms per day of hydrazine or a little less than 2½ kilograms per day of water, using water electrolysis O_2H_2 gas propulsion, or about 5½ kilograms per day of CO_2 if the latter is electrically heated to develop a specific impulse of about 170 seconds.

The available CO_2, if CO_2 is not recycled within the ECLSS system, is spotted on the chart at the level of the hydrazine equivalent. Thus, the available CO_2 would nearly always be sufficient to maintain the orbit in the low inclination case and about half the time sufficient in the high inclination case.

Table 9. Orbit Altitude

SOC Studies:

Altitude was limited to 370 km by shuttle performance without OMS kit.

New Options:	**East**	**Polar**
Direct insertion –	500 km	400 km

TMS & crew cab – any altitude permitted by radiation (about 600 km).

Space station must be at same altitude as serviced spacecraft for on-demand servicing.

500 km is above most UV air glow – important for space telescope.

Greatly enhances space station utility for observatory servicing.

500 km reduces drag by an order of magnitude compared to 370 km.

Orbit makeup could use resistojet/ECLSS surpluses

Supplement with O_2/H_2 for densest atmosphere.

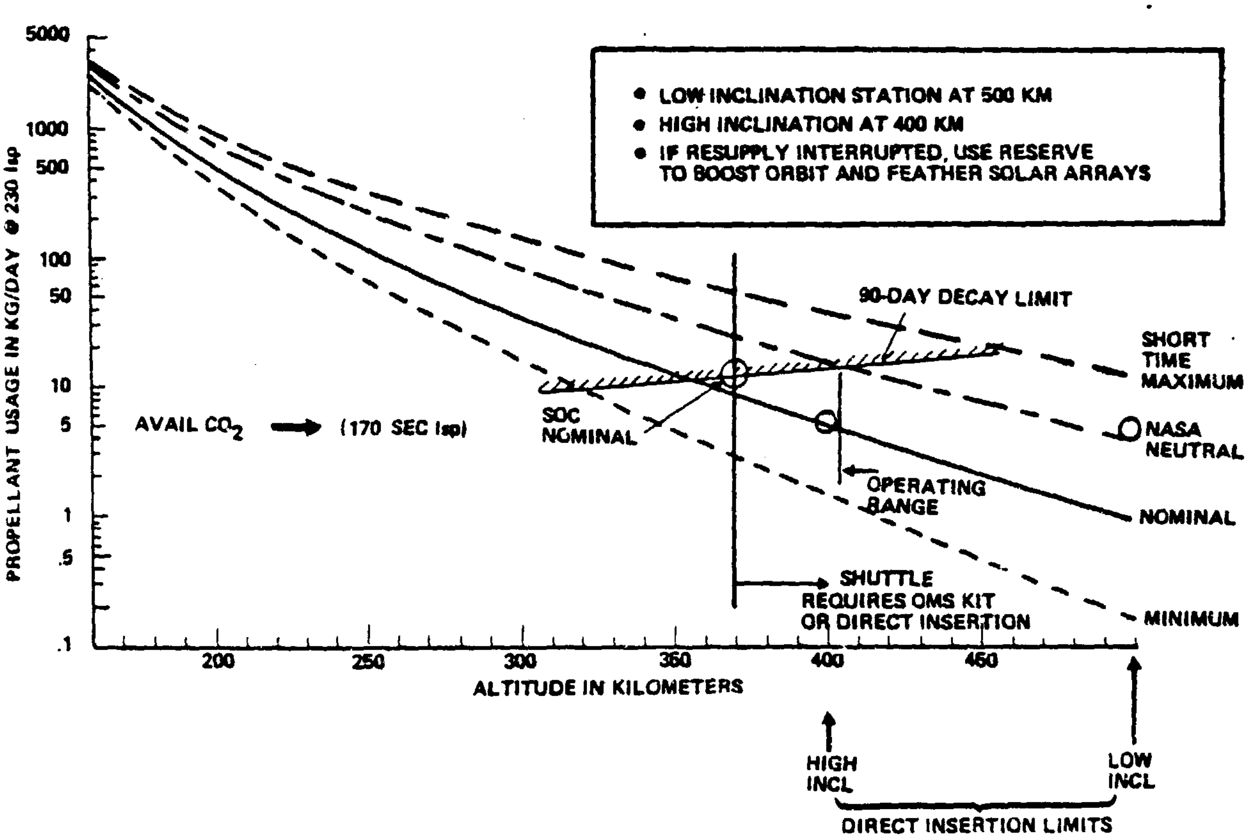


Figure 21. Propellant Usage vs. Altitude (8-Man Station at 50kW)

SPACE STATION ARCHITECTURAL OPTIONS

The overall system architecture needed by the year 2005, according to our mission needs results, includes space stations at low and high inclinations with several commercial micro-gravity production platforms, a cluster of astrophysics free-flyers and an astrophysics platform. In addition, OTV's are used to deliver payloads in high altitude orbits and TMS's are used for relative access between the set of space stations and formation flying vehicles in low inclination orbit.

The shuttle provides Earth-to-space transportation.

The overall architecture is displayed in figure 22.

tions long before mission requirements were clarified and quantified. The analogy points out that many influences on space station architecture arise from constraints and factors other than mission accommodations. These constraints were taken into account throughout our architectural studies.

A further aid to architectural development was the list of generic space station elements expected to be present in almost any space station architecture, presented in table 10. This list was derived from earlier studies and from evaluation of available space station requirements data from the SOC studies. This list assisted us in developing the elements of space station architecture.

Our architectural options definition began by dividing the architectural options into

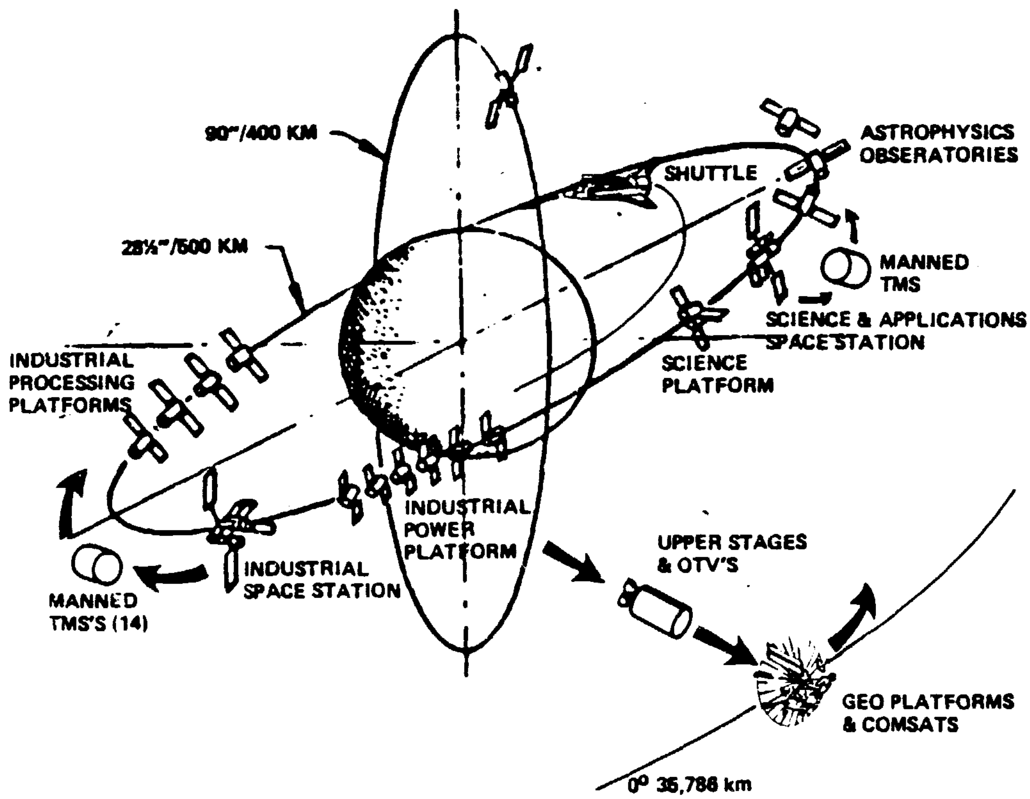


Figure 22. Eventual Architecture-Year 2005 (Scenario A-Mission Driven)

Early in the space station study we struck an analogy between the architecture of speculative office buildings as illustrated in figure 23, and space station architecture, as in figure 24. This analogy enabled us to begin space station architectural investiga-

open and limited classes. The open class accepted any technically feasible idea. It included such things as external tank-derived space stations, tether concepts and large space stations launched on shuttle-derived launch vehicles.

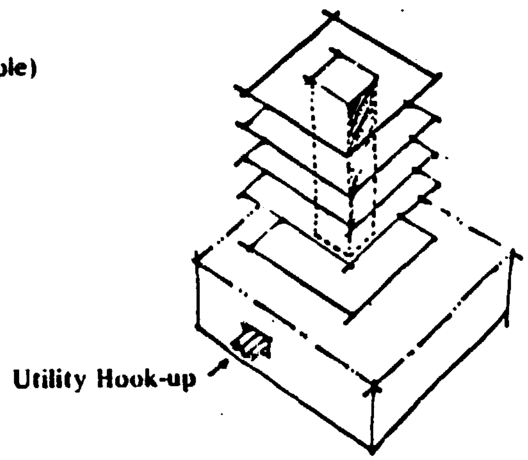


Figure 23. Speculative Office Building Architecture

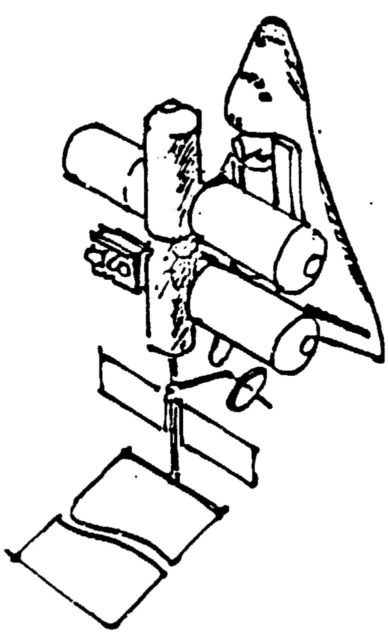


Figure 24. Space Station Architecture

The limited class was derived from a premise. The premise was succinctly stated by James Beggs last summer. It is included in figure 25 and states that the space station is permanent, manned, small at first, and assembled and serviced by the space shuttle. This premise places many constraints on the space station. One of these, permanency, is illustrated along with the premise in the figure. The diagram shows how the attribute of permanency, combined with orbit altitude limitations and solar array power requirements, leads to the sizing of an orbit makeup propulsion system.

As we reviewed the open class options illustrated in figure 26, we found problems that led to our decision not to recommend them for early space station.

Table 10. Generic System Element List

- Habitat Module
- Command & Control Module
- Service Module
- Laboratory Module
- Supporting Elements
  - Docking tunnel
  - Airlock module
- General purpose support equipment
  - Mobility/access systems
  - Handling equipment
  - EVA work station
  - Turntable/tilt table system
  - Umbilical system
  - Storage systems
- Construction support equipment
  - Cherrypicker
  - Manipulator module
- Transportation support equipment
- Resupply and logistics support systems
  - Logistics module

OPEN	LIMITED
● SHUTTLE EXTERNAL TANK ● TETHERS ● SHUTTLE DERIVED LAUNCH VEHICLE	"I BELIEVE THAT OUR NEXT LOGICAL STEP IS TO ESTABLISH A PERMENENT MANNED PRESENCE IN LOW-EARTH ORBIT. THIS CAN BE DONE BY DEVELOPING A MANNED SPACE STATION. IT WOULD BE SMALL AT FIRST, ASSEMBLED IN ORBIT WITH MODULES CARRIED TO SPACE BY THE SHUTTLE. JIM BEGGS, JUNE 23, 1982 —FROM A SPEECH TO THE DETROIT ECONOMIC CLUB

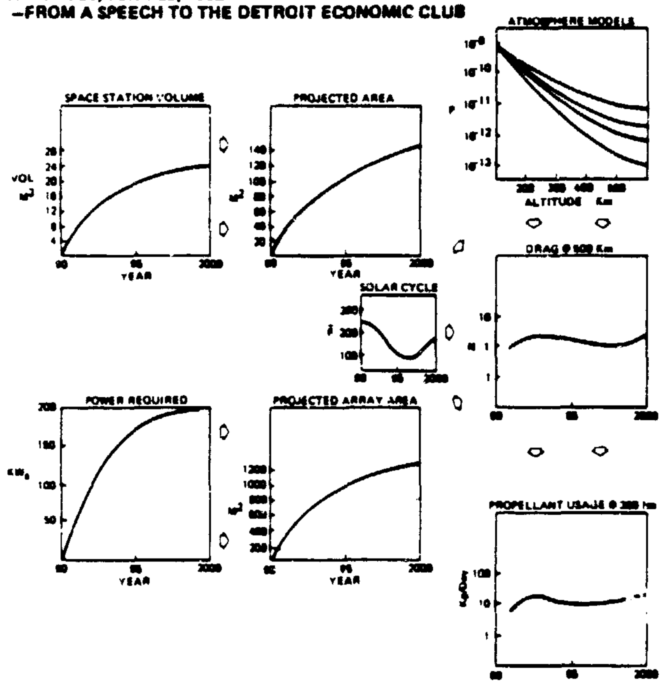


Figure 25. We Studied Two Classes of Architecture

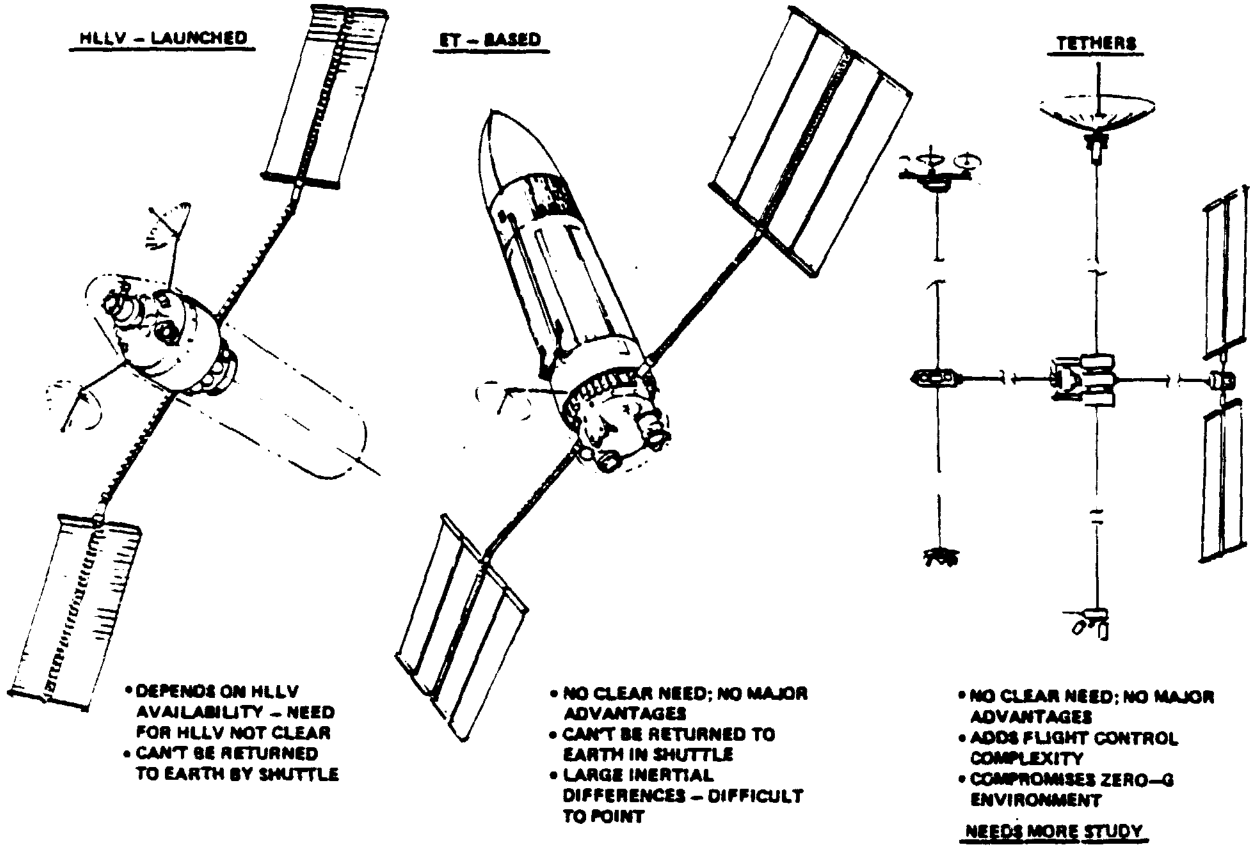


Figure 26. Architecture Options Not Recommended

A heavy lift launch vehicle would permit orbiting a capable space station on a single flight. However, such a system depends on availability of the launch vehicle, for which the timing is presently unclear. Further, such a large system could not be returned to the Earth by space shuttle if required for overhaul or major repairs.

Similar objections were found regarding space stations based on external tanks. A modest space station can be designed into the aft cargo compartment space of the external tank, providing a relatively commodious habitat. However, we found no clear need or major advantages. Like the HLLV-launched space station, this one can't be returned to Earth. It tends to have less redundancy and backup capability in pressure volumes than modular designs. Finally, the external tank itself is a large object with great inertial differences. Such a system is difficult to fly inertially-oriented as needed for some of the scientific missions. We concluded that for the configuration depicted, approximately 20 Skylab CMG sets would be needed to maintain inertial orientation.

There is a great deal of interest in tether concepts. Tethers offer special capabilities not readily obtained in other ways. However, based on the mission requirements we identified, we found no major advantages for tethers. A tethered system adds flight control complexity (an issue already high on the problem list). Most of the tethered concepts would compromise the zero G environment necessary for materials processing and life sciences investigations.

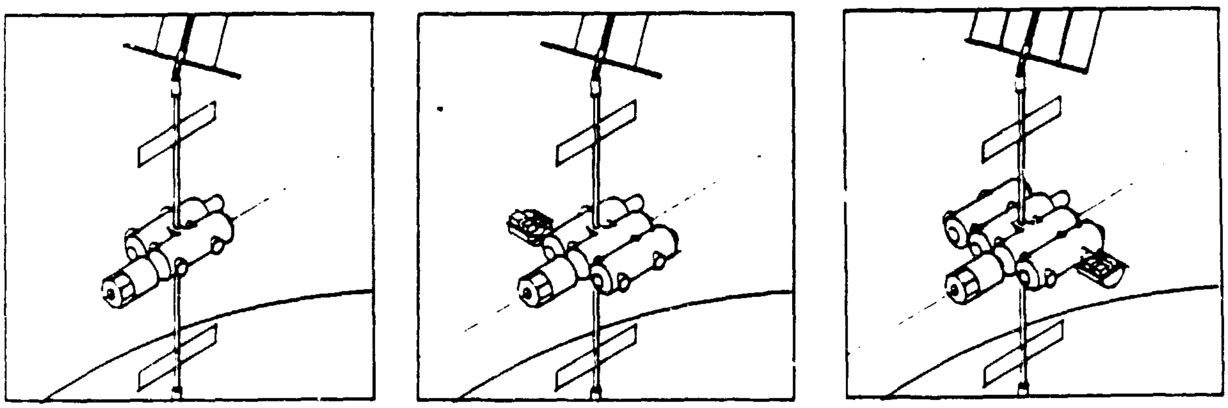
Tethers could provide an economical means of obtaining partial-G environments, important to some life sciences research. Tether systems need further study, but are not now recommended as a baseline architecture for an early space station.

We began our study of the limited-class architectures by examining alternative means of growth. Growth approaches are important inasmuch as the early space station will probably accommodate four people, whereas the end-point system may need to accommodate as many as 15 to 20. Similarly, laboratory and other facility modules will be added, solar array power must be

increased, and accommodations for mission payloads must increase.

We identified three generic means of growth: planar, branched, and three-dimensional. These three growth concepts and their pros and cons are summarized in figures 27, 28, and 29. The planar growth means was selected as the most practical and safest option.

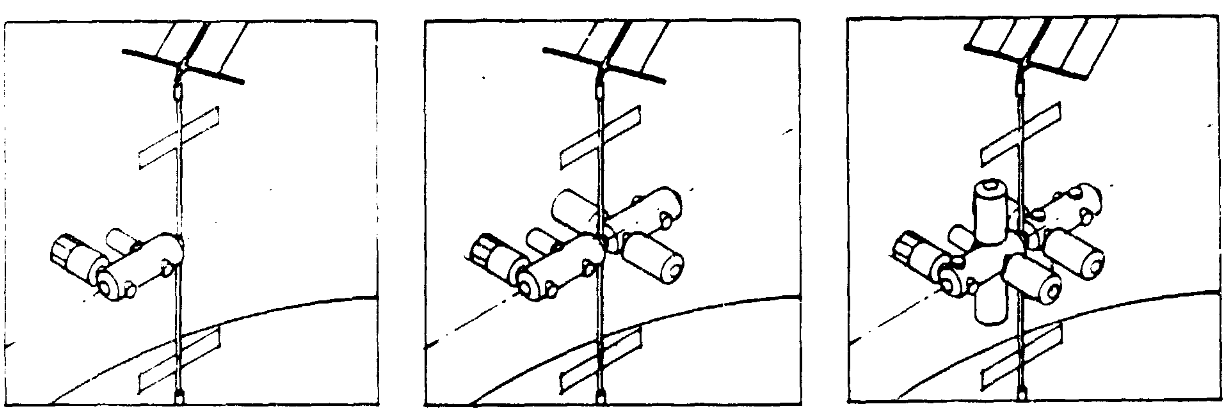
Our discussions with representatives of companies from other nations indicated potential foreign contributions to an international space station program as listed in table 11. We attempted to make our architectural approaches compatible with such foreign contributions in the event the United States decides to undertake a program with international content.



PRO
- AMPLE WORK SPACE FOR OPERATIONS
- TWO OR MORE EGRESS PATHS
- CAN BE ASSEMBLED BY SHUTTLE/RMS
- FAIR TO GOOD THERMAL VIEW FACTOR

CON
- INERTIAL DIFFERENCE OUTGROW CMG
- CAPABILITY FOR INERTIAL ORIENTATION
- EARTH ORIENTATION RESTRICTED TO STATION PLANE IN ORBIT PLANE
- LIMITED GROWTH

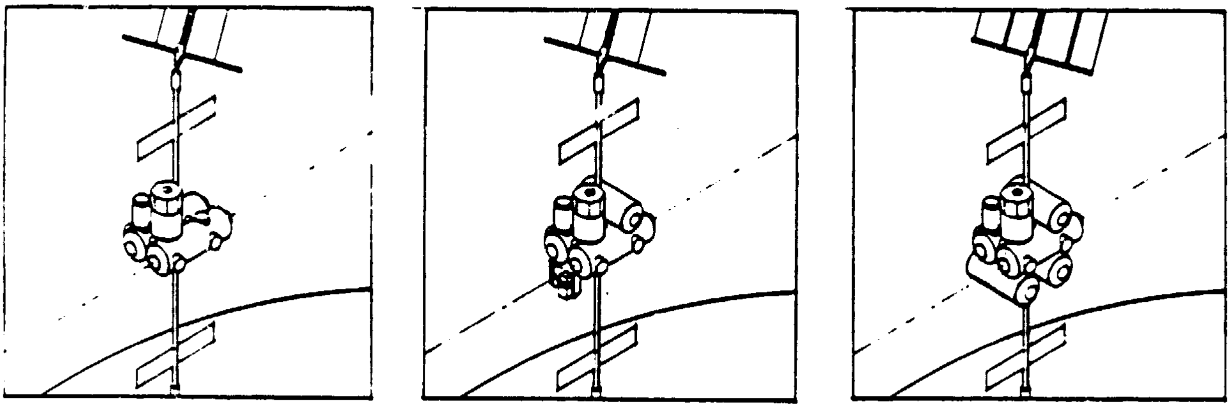
Figure 27. Planar Growth



PRO
- CAN GROW INDEFINITELY
- MORE FLEXIBLE FOR INSTRUMENT POINTING AND ATTACHMENT
- FAIR TO GOOD THERMAL

CON
- OPERATIONS WORK SPACE CUT UP—MOBILITY DIFFICULT
- LACK OF DUAL EGRESS PATHS VIOLATES JSC SAFETY RULE
- TENDS TOWARD LARGE INERTIA DIFFERENCES

Figure 28. Branched Growth



PRO
- TWO OR MORE EGRESS PATHS
- INERTIAL SYMMETRY PERMITS ALL ORIENTATIONS

CON
- OPS WORKSPACE RESTRICTED; MOBILITY DIFFICULT TO IMPOSSIBLE
- DIFFICULT TO ASSEMBLE, BUT RMS REACH OK
- POOR MODULE SURFACE THERMAL VIEW FACTORS
- GROWTH IS LIMITED

Figure 29. 3-Dimensional Growth

Table 11. Typical Foreign Inputs

Canada	–	Manipulator arm
ERNO	–	Lab modules Resupply?
BA/Telefunken	–	Solar array
Dornier	–	Instrument pointing system Thermal control Crew accommodations
Aeritalia	–	"Can" structures
Japan	–	Robotics Resupply? Lab module Free flyer platform

The result of our architectural investigations was three recommended space station architectures. One is an <u>incremental</u> approach that provides a maximum of flexibility and adaptability for both high and low inclination orbits (and even high altitude orbits). The flexibility is provided through a number of different types of modules. The second approach was a <u>unified</u> approach that emphasized maximum commonality between modules, permitting more rapid growth for

the low inclination space station, but sacrificing capability to operate in high inclination orbits because of the mass of its unified module.

Finally, we developed a derivative free-flyer platform derived from manned space station architectural elements. The derivative version is not described in this summary report.

We developed a great degree of design detail. This was needed to support cost analyses as well as mass properties, inertia, and space shuttle center of gravity compatibility assessment. These details were necessary to verify the viability of the basic design strategies. The significance of these architectural options is in the underlying design strategies and not in the details. The details represent point designs based largely on our prior experience on earlier and concurrent space station studies, on engineering judgement, and on technology considerations. Our design details were not supported by the full array of trade studies that would be necessary to finalize space station configurations at the level of detail depicted.

Figure 30 illustrates the incremental architecture arranged for high inclination operations. The service module would be launched on the initial shuttle flight. The next flight would deliver the command and control module. A third would deliver the logistics module and permit initial manning of the space station with a crew of two or three. A fourth flight would deliver the habitat module to permit increasing the crew size to four and allowing more generous crew accommodations. Mission payloads, tunnels, and airlocks would be delivered on additional flights. Depending on the weight of the logistics module, the airlock could probably be delivered on the logistics module flight.

These modules are sized to permit their launch singly to high inclination orbits and two at a time to low inclination orbits where the shuttle has a much greater lift capability.

Figure 31 shows a somewhat larger version of the incremental high-inclination station.

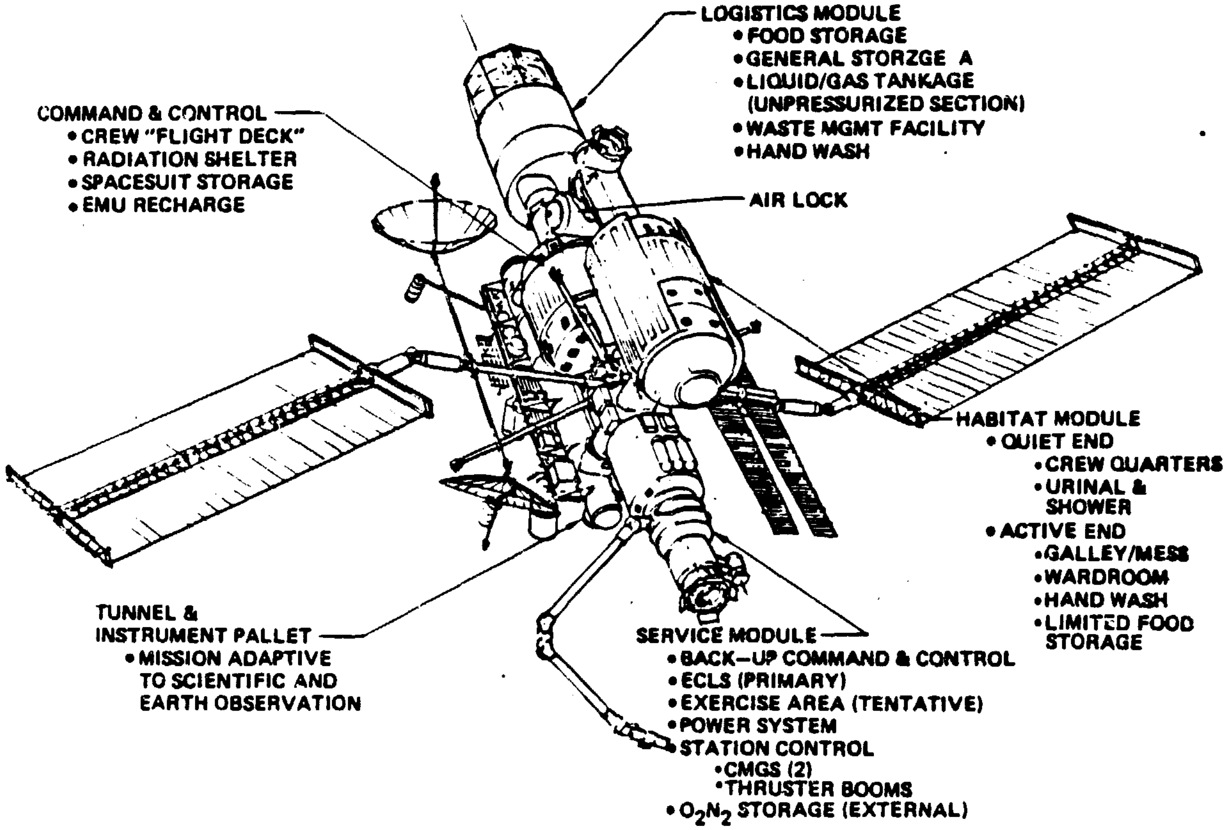


Figure 30. Incremental Architecture

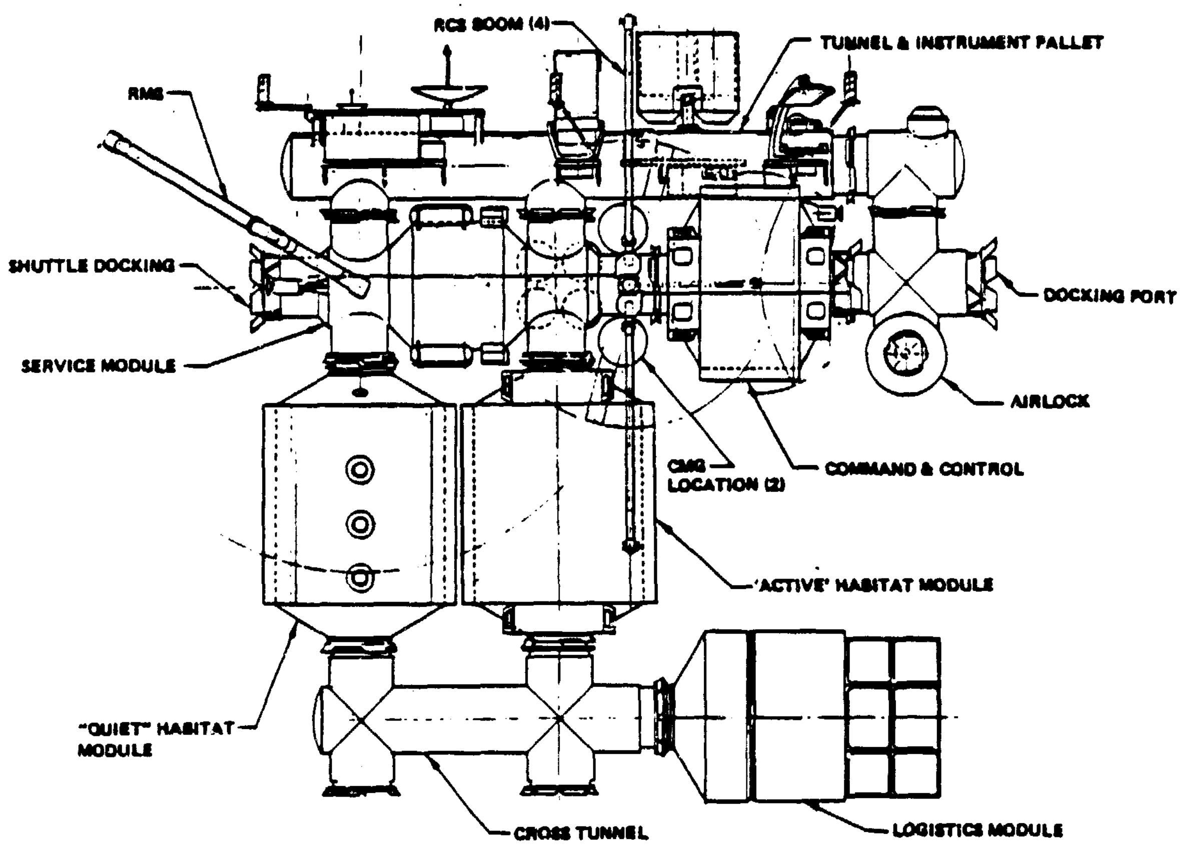


Figure 31. Incremental Architecture (Orbital Plane View)

This configuration might be used, for example, if national security applications in this orbit required additional crew members (beyond the four identified for science and applications missions).

The evolutionary end-point for the incremental space station, sized to house a crew of 15 people, to provide adequate laboratory space, and to provide servicing of upper stages is illustrated in figure 32.

The evolutionary end-point depicted needs further analysis to assess compatibility with required construction operations, and practicality from the standpoint of station assembly, shuttle docking clearance, inertias, and other operational factors. Based on our SOC experience (which dealt with substantially larger modules), we do not believe that there are any problems with this system in these areas, but the necessary analytical procedures have not been accomplished.

The unified space station architecture shown in figure 33 relies on a single major module configuration to provide both habitat, work and laboratory space. The only other space station module required is a logistics module. Smaller articles include platforms for mounting mission equipment and upper stage servicing areas.

The unified module is too massive to be launched to a high inclination orbit, except by a shuttle derivative cargo launch vehicle.

The comparatively large size of the unified architecture module permits a relatively capable space station to be built up from relatively few modules and shuttle flights. This is shown in figure 34.

Note the use of side-berthing to provide multiple egress paths and utility connections between modules.

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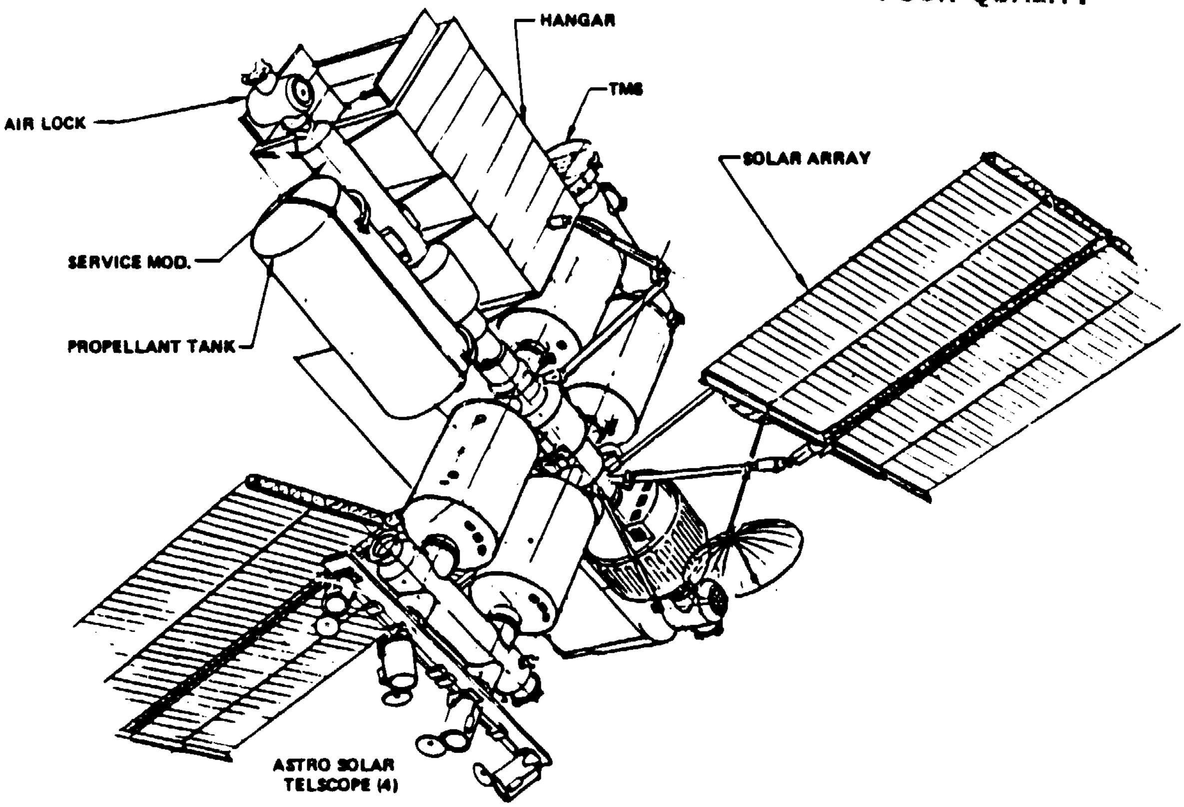

Figure 32. Incremental Space Station Evolution End Point (Low Inclination)

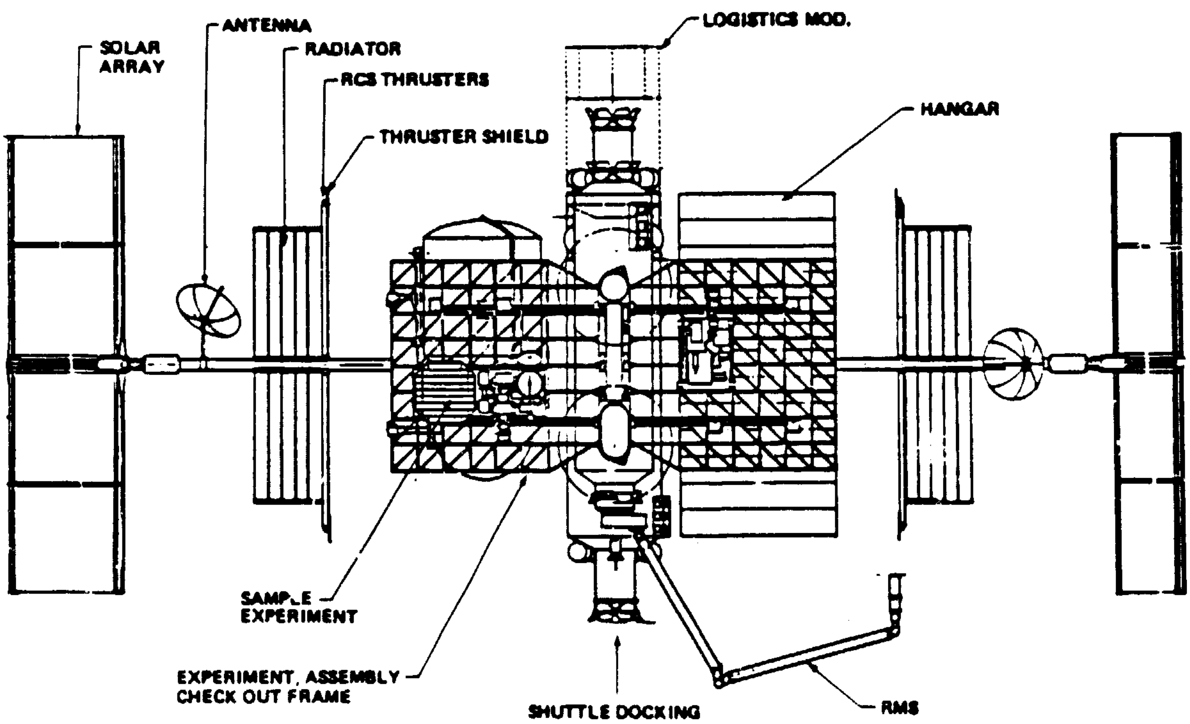

Figure 33. Unified Space Station (Earth Facing View)

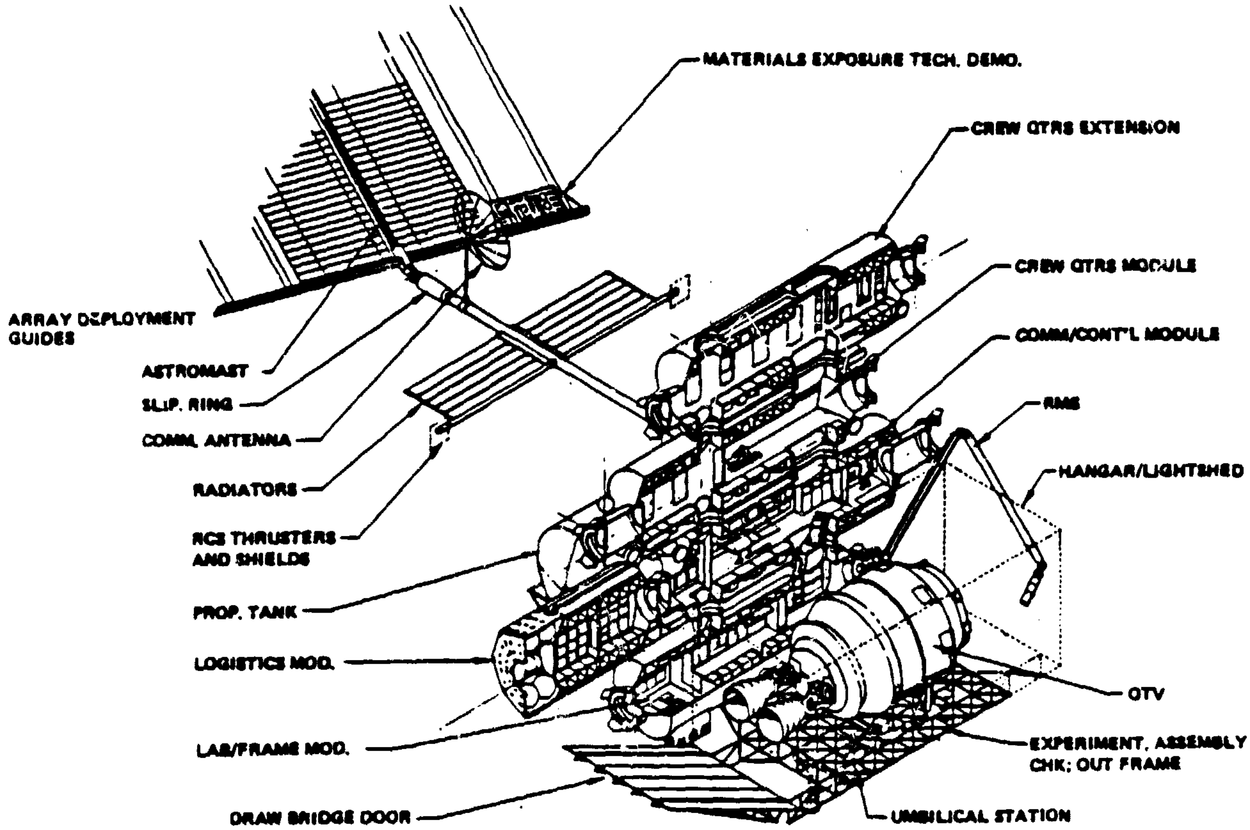

Figure 34. Cutaway View of Unified Space Station Architecture

MASS PROPERTIES COMPARISON

Mass properties summaries are presented in table 12 for the incremental architectural service module and command module, and the unified architecture module. These summaries are based on detailed weight estimates to be provided as a part of the study documentation. Growth was allocated as 33% of identified weight excepting for the cabin shell and the mission equipment. The cabin shell was not included in the growth estimate because the wall thickness is sized for collision protection. The mission equipment was not included because it is relocatable.

CENTER OF GRAVITY STRATEGY

The permissible center of gravity limits of the shuttle payload bay for heavy payloads are quite narrow. The envelope is illustrated in figure 35 together with approximate lengths and shapes of the service module and command module for the incremental architecture. Also shown is a docking module required in the payload bay if the shuttle is to dock or berth with a space station. Mass of this docking module was estimated by Rockwell in the Space Operations Center studies as 4,000 lbs. or 1.85 metric tons. The service module and command module weights are variable depending on location and disposition of mission equipment and the quantity of orbit makeup propellant loaded into the system for the initial launch. By shifting the relocatable mission equipment into the command module for launch the combined CG range can be brought within the shuttle CG envelope.

The strategy for complying with shuttle mass and CG limits for the incremental and unified architectures for low inclination and high inclination is further elaborated in table 13. Weights presented are in pounds in view of familiarity with shuttle performance capabilities in terms of pounds of transportation weight.

Table 12. Mass Properties Comparison

Item	Incremental Architecture				Unified Architecture	
	Service Module		Command Module		Standard Module	
	kg	lb	kg	lb	kg	lb
Structures	3562	7852	2981	6571	6798	14987
Cabin Shell	3104	6843	2142	4722	4236	9339
Other	458	1009	839	1849	2562	5648
Mechanisms	546	1203	164	361	408	899
Thermal Control	684	1507	831	1832	1364	3007
Auxiliary Prop	919	2026	0	0	587	1294
Ordnance	12	26	32	70	10	22
Electric Power	2609	5751	270	595	3478	7667
GN&C	720	1587	100	220	420	926
Tracking & Comm.	440	907	248	546	653	1440
Data Management	175	385	568	1252	481	1060
Instrumentation	100	220	36	79	100	220
Crew Accommodations	0	0	50	110	306	675
EC/LSS	829	1827	1475	3251	1911	4213
Mission Equipment	3026	6671	705	1554	1844	4065
Fixed	524	1155	73	160	100	220
Relocatable	2502	5516	632	1394	1744	3845
Growth	2690	5930	1522	3355	3854	8497
TOTAL	16312	35961	8982	19801	22214	48973

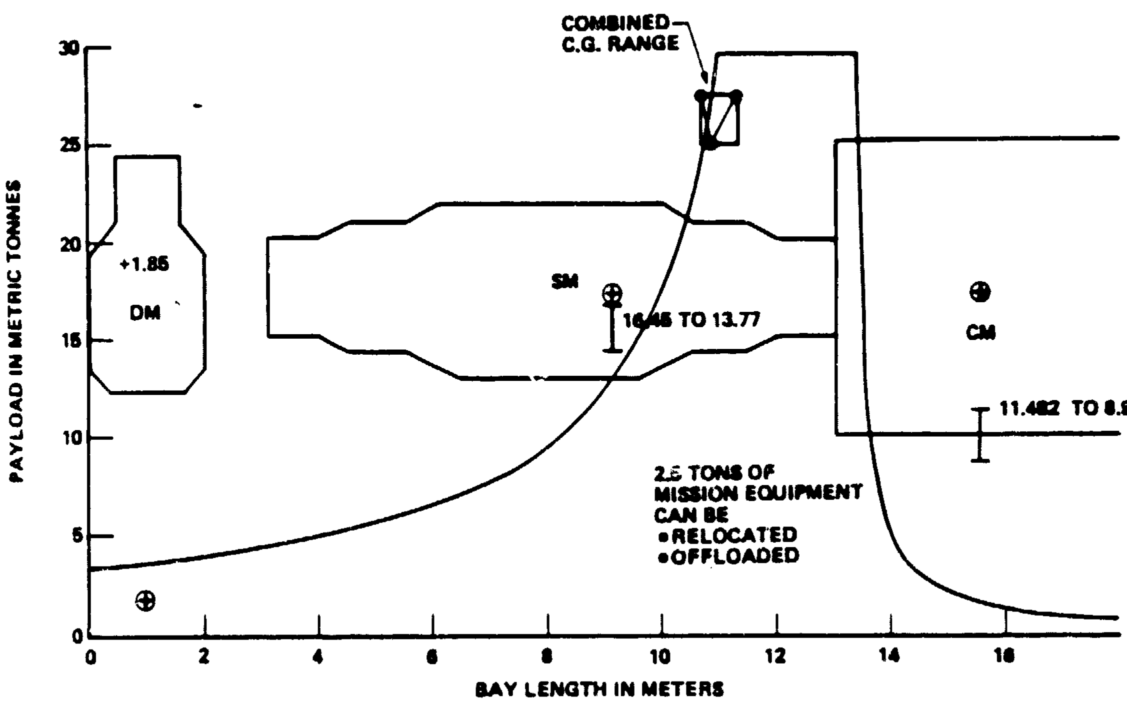

Figure 35. Center of Gravity Strategy

Table 13. Mass and CG Strategy

OPTION	AS WEIGHED	LOW INCLINATION		HIGH INCLINATION	
		CHANGES	MASS	CHANGES	MASS
INCREMENTAL					
SERVICE MODULE	35,981 LB	MOVE 5,000 LB MISSION EQUIPMENT TO CM	30,981 LB	DELETE M.E. LAUNCH W/O DM	30,981 LB
COMMAND MODULE	19,801 LB		24,801	DELETE M.E. ADD RADIATION SHELTER	31,000 LB *
STD 7-METER MODULE	24,500 LB *	LAUNCH 2 - ALL M.E. IN AFT	49,000 LB	LAUNCH 1	24,500 LB
UNIFIED	48,973	LAUNCH WITH HEAVY END AFT	48,973	NOT APPLICABLE	

* ROUGH ESTIMATE. DETAILED MASS ESTIMATE NOT PREPARED

TECHNOLOGY SELECTION

Our principal subsystem technology recommendations for high leverage technology advancement are presented in table 14. Subsystem technology recommendations were developed utilizing a matrix procedure in which technology selection interrelationships as well as mission orbit altitude and growth considerations were considered. The

Table 14. Technology

High-Leverage Items

- Integrated O_2-H_2 (gas) system for electrical energy storage and propulsion.
- Data Management - Packet-switching redundant networks, fiber optics. Use the best available state-of-the-art.
- EC/LSS water loop closure to minimize resupply requirements important for high-inclination missions.
- Communications Bandwidth - Provide for growth to millimeter-wave and laser com.
  - Set the "requirement" at what the state of the art can deliver - Don't let it be a cost driver.
  - Be wary of specifying digital color TV. State of the art questionable. Potential cost driver.
- Long life thermal coatings and alleviation of thermal coating degradation problems through use of thermal storage and steerable radiators.
- Automated housekeeping subsystems - Integration of automated electrical, thermal and ECLSS subsystems using expert system techniques.

complete matrix appears in volume 4 of our final reports.

One item on the facing page merits further discussion. It has been popular in the past couple of years to consider incremental closing of the EC/LSS water and CO_2 loops. This is argued to save money in early years when crews and hence resupply requirements may not be large. However, we recommend closing the water loop initially to minimize resupply requirements because this turns out to be very important for the high inclination missions where shuttle flights will be infrequent and lift capability is small.

A second reason for this recommendation is that if the engineering and integration required to close these loops is deferred until some hardware is in space, we may discover integration problems very difficult to solve by retrofit techniques. We believe that such deferrals of basic developmental and integration engineering create high technical and cost risks for the program. This consideration outweighs the relatively modest savings that might be achieved by deferring water loop closure.

One need not, of course, operate in the fully closed mode until the equipment and water purity are flight-proven.

There are several additional technology issues that merit discussion as noted in table 15.

Our space station configurations utilize Astro-mast deployable solar arrays on masts to place the solar array away from the immediate space station operational area and to reduce solar array shadowing for Earth-oriented station operation. This leads to structural modes with frequencies less than 1/10 Hertz, and has raised concern that precision pointing of instruments from such a soft structure may be difficult or impossible. The issue needs further assessment, but at present pointing goals appear within reach. Further study and assessment are needed before we accept space station configuration compromises simply to increase stiffness.

We continued to assess external tank scavenging. It appears to be feasible as well as desirable for the era when the orbit transfer vehicle is space based. However, it is not attractive as an alternative to solar array power. Using scavenged propellants with fuel cells would result in severe resupply requirements during a time when it is important to minimize space station demands on space transportation. It should be further noted that earlier estimates of space station power requirements are less than mission needs estimates would indicate.

We believe that autonomy and automation, as well as standardization, have high leverages on initial and life-cycle cost for the reasons stated.

To get a better appreciation for the stiffness issue, we conducted an initial evaluation of controller bandwidth requirements to achieve given attitude stabilities. Our nominal pointing stability goal is 5 arc seconds. We find that if the controller bandwidth is restricted to frequencies significantly below the solar array nodal frequencies determined for the SOC, the 5 arc seconds cannot be obtained unless one uses an instrument subplatform like the Dornier IPS to improve instrument pointing, as shown in figure 36. Further analysis is needed to assess the degree to which solar array stiffness can be increased without making major configuration concept changes. Potential avenues include rigid panels instead of Astromast-deployed panels, and using stays and spreaders to increase mast stiffness.

One mission need frequently stated by users was for a low contamination environment. One approach is to put contamination sensitive systems on a free-flyer platform. This, however, complicates servicing operations and requires EVA for essentially all servicing.

We considered several measures to reduce space station contamination environments to a level acceptable for mission operations, as tabulated in table 16. Orbit makeup propulsion could be provided by resistojets using either hydrogen or EC/LS surpluses. At the 500-kilometer altitude for the low inclination station, infrequent orbit makeup maneuvers at higher thrust could utilize the integrated hydrogen/oxygen system we recommended.

Table 15. Other Technology Issues

• **Stiffness and Flight Control**
  • **This issue needs further assessment. Pointing goal appears within reach.**
• **ET Scavenging**
  • **Appears feasible and desirable for space-based cryo OTV**
  • **Not attractive as an alternative to solar array power**
• **Autonomy and automation - High leverage on life cycle cost**
  Automation should be used to reduce crew workload and eliminate dependence on large cadre of ground mission controllers. Put the flight crew in charge (like an airplane crew).
• **Standardization - High leverage on life cycle cost**
  • **Use industry standard hardware and software wherever practical. Space qualify as necessary.**
  • **Unique/special designs require support of spares program over life of program.**

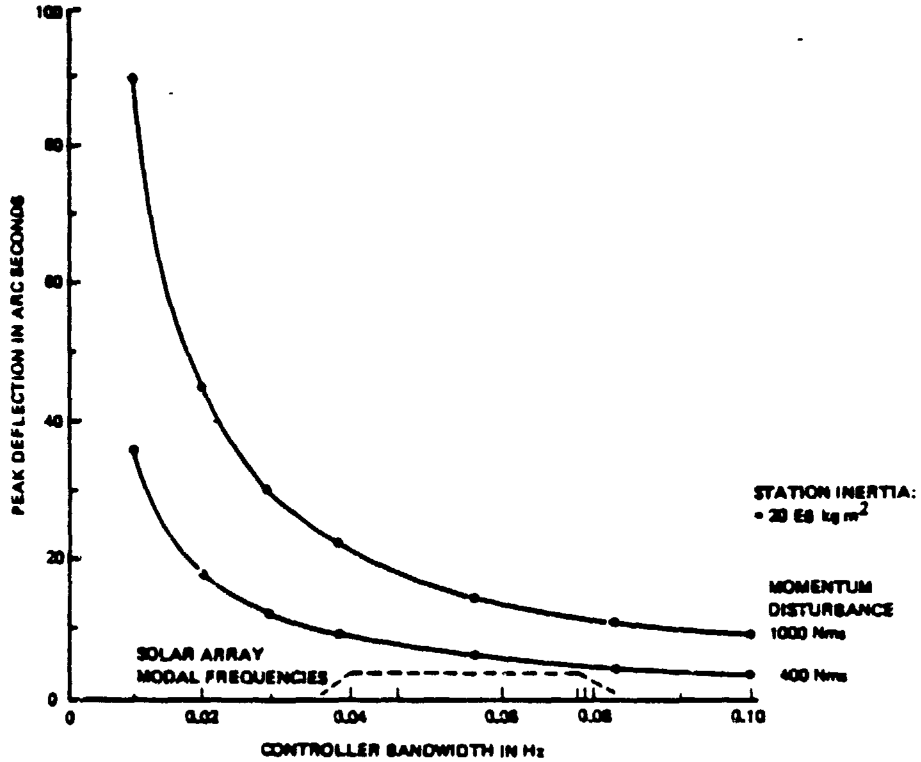

Figure 36. Space Station Deflection as a Function of Controller Bandwidth

Airlock outgassing is a source of contamination. Even though airlocks will be pumped down to conserve atmosphere, the minimum practical pressure will be 1/2 to 1 psi. When the airlock door is open, outgassing will emanate from the airlock walls for a significant time. It is important to locate airlocks to eliminate direct paths from the airlock

Table 16. Contammination Strategy

• Resistojets using H_2 and EC/LS surplus
• Location of airlocks
• Ice pack suit
• No vent toilet
• Low leakage design
• CMGs

interior to sensitive instruments.

Elimination of the water boiler from the EVA suit is important. Also, the present shuttle toilet vents water vapor and other contaminants overboard. We need a no-vent toilet.

Pressurized modules should be designed for low leakage. Historically, space station leakage specifications have been set at the resupply nuisance level, e.g. several kilograms per day. The leakage specification should be reduced to that consistent with good manufacturing and quality control.

The space operations center concept employed a principal-axis flight mode that was normally gravity stable together with attitude control thrusters to provide control authority when needed. The combination of need for low contamination and precision pointing leads to a requirement to provide control moment gyros on the station for normal attitude control operations reserving the use of thrusters for situations when high control authority is needed.

PROGRAM PLANNING

Our cost estimates for space station were derived assuming conventional space practices, i.e. we used a history-based parametric cost model without imposing any special assumptions. There is, however, evidence that significant cost savings might be achieved relative to our nominal estimates.

Our estimates assumed adequate definition; that is, we did not include cost penalties for excessive change activity. We also assumed that requirements that stressed the available state of the art would not be accepted.

Parametric cost models include environment or "platform" factors that skew the cost estimate. In the RCS PRICE model, "manned space" is the most costly environment of all. Other environments such as unmanned space or military aircraft are much less costly. This suggests that a careful review of specifications, standards and practices should be carried out to identify and eliminate those that are more costly than the benefit they provide.

Autonomy and maintainability will have such a large impact on life cycle cost that improper attention to either could negate space station economic benefits, which hinge on reasonable operational costs. Similarly, specification of a unique design where an industry standard could serve will have a severe impact on cost of maintaining a spares program. The issue is not new versus old technology, but how widely spares production and sustaining engineering costs are shared.

Finally, we were exposed to one study that indicated thirty percent of the cost of a typical government program was in compilation of reports. The implication was that these were reports specified by contracts but not essential to accomplishment of the programs.

A summary of cost drivers is presented in table 17.

The costing assumptions we used are summarized in table 18.

We updated all of our space station cost estimating data base to 1984 dollars and plotted the results as shown in figure 37. This permitted the use of high-level curve fits to estimate the costs of modules such as airlocks that were not estimated in detail. These data include modules defined by the SOC study, Boeing IR&D, and the present space station study.

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Table 17. Cost Drivers Summary

ITEM	IMPACT ON DDT&E	IMPACT ON INVESTMENT	IMPACT ON SPARE & SUPPORT	IMPACT ON OPERATIONS	COMMENTS
INADEQUATE DEFINITION; EXCESSIVE REQTS	? BUT HIGH	? BUT HIGH	? BUT HIGH	? BUT HIGH	SOME COMPARISON STUDIES HAVE SUGGESTED FACTOR OF 2 BUT NO REAL BASIS TO COMPARE
SPECS AND STANDARDS	100%	100%	MODERATE	LOW	
AUTONOMY	LOW TO MODERATE	LOW	MODERATE FAVORABLE	VERY HIGH FAVORABLE	FAILURE TO IMPLEM IT COULD NEGATE SPACE STATION BENEFITS
UNIQUENESS VS INDUSTRY STANDARD	10%	10%	FACTOR OF 2 TO 5	?	ISSUE IS NOT NEW VS OLD TECHNOLOGY
PAPER	30%	30%	?	?	
MAINTAINABILITY	10%	10%	LOW	HIGH TO EXTREME	FAILURE TO IMPLEMENT COULD NEGATE SPACE STATION BENEFITS

Table 18. Costing Assumptions

1984 dollars
No schedule problems
Good definition
Normal specs and standards
Industry standard where practical
Normal paperwork
25% spares
2½ sets support equipment
Support equipment complexity factor 1.5
SE&I and ground test complexity factor 2.0
One prototype production unit used for integration testing

Data are presented as defined in the parametric cost models, i.e. as DDT&E and unit costs.

Hardware acquisition and other costs are summarized in table 19. In this tabulation, manufacturing costs associated with DDT&E have been transferred to the DDT&E column. A nominal contractor fee of 10% has been added (most cost models estimate cost, not price). These include a test unit for each module and nonrecurring manufacturing costs such as tooling.

Additional DDT&E charges are shown for subsequent unit acquisition, recognizing that these will not be identical to prior units. The additional charges were roughly estimated as 25% of the initial DDT&E.

A variety of "other" costs must be included in a complete program estimate. Some of these can be only roughly estimated at the present time. Those we have identified are listed on the right of the figure.

Initial costs of four architecture/program scenario options were estimated as summarized in table 20. "Other" costs were included, as were considerations of numbers of hardware units required.

The "bare bones" program provides a permanent manned presence in space, but little else. The space station utilizes the incremental architecture without dedicated habitat or lab modules. It represents the minimum feasible space station program.

The program-constrained architecture paces space station buildup based on projected space station funding availability rather than onset of mission needs as projected by the mission needs analysis. The initial cost of this program is within the range of the

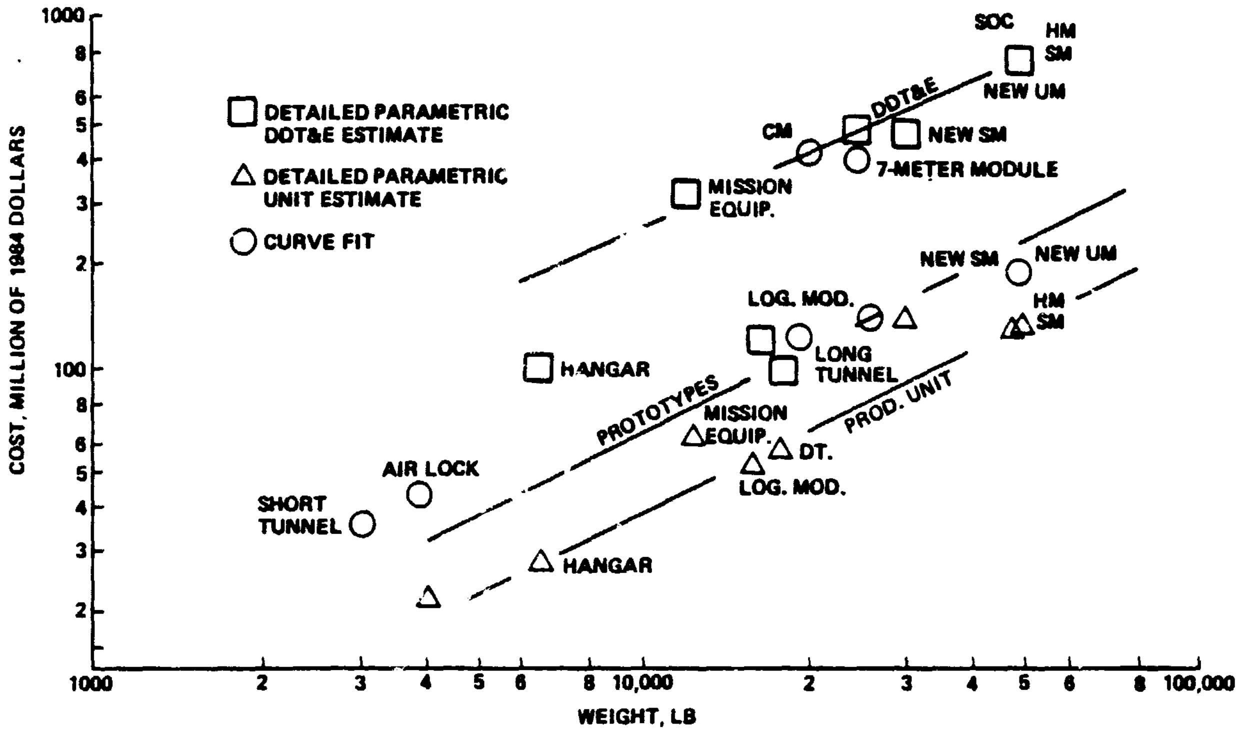

Figure 37. System-Level Cost Relationships

Table 19. Cost Estimates Summary (Values in Millions of 1984 Dollars)

HARDWARE ACQUISITION (INCLUDES FEE)						OTHER COSTS	
INCREMENTAL ARCHITECTURE			UNIFIED ARCHITECTURE				
ITEM	DDT&E*	INVEST.	ITEM	DDT&E	INVEST		
SERV. MOD.	725	165	UNIT MOD NO. 1	1250	220	SIL LAB(S)	60
C&C MODULE	670	130	UNIT MOD NO. N	315	220	PROGRAM-LEVEL INTEGRATION	10%–20%
AIR LOCK (2)	85	50	AIR LOCK (2)	85	50	FLIGHT SOFTWARE	100
7-METER NO. 1	710	165	LOGISTICS (2)	240	121	MISSION EQUIP	
7-METER NO. N	180	165	HANGAR	165	35	SUITS, TOOLS, ETC SCIENCE, ETC.	? ?
SHORT TUNNEL	50	12	PROP STOR.	280	210	SUPPORT CONTRACTS	?
HANGAR	165	35	CONSTR EQUIP	350	165	TRAINING & SIMUL	?
PROP STOR.	280	210				SHUTTLE FLIGHTS	71
CONSTR EQUIP.	350	165				CIVIL SERVICE	?
						CONTINGENCIES	30%

*INCLUDES TEST HARDWARE & NONRECURRING MANUFACTURING

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Table 20. Initial Costs of Alternative Program Scenarios (1984 Dollars)

	INCREMENTAL ARCHITECTURE				UNIFIED ARCHITECTURE*
	BARE BONES PROGRAM (LOW INCL)	PROGRAM CONSTRAINED (LOW INCL)	MISSION DRIVEN		MISSION DRIVEN (LOW INCL)
			LOW INCL	HIGH INCL	
SERVICE MODULE	890	890	890	165	0
COMMAND MODULE	800	800	800	130	0
7-METER MODULES	0	1220	1220	345	2540 (3 UNITARY)
AIRLOCKS	135	135	135	100	135
TUNNEL	0	62	74	0	0
LOGISTICS MODULES	360	360	360	120	360
SIL LABS	60	60	60	20	50
FLIGHT SOFTWARE	50	100	100	50	100
LABS	0	0	690	0	0
MISSION EQUIPMENT	100	200	300	100	300
OTHER	100	200	200	100	200
SHUTTLE FLIGHTS	140	285	425	285	355
PROGRAM INTEGRATION	265	650	790	210	610
TOTAL	2900	4962	6044	1625	4650

*DOESN'T SUPPORT HIGH INCLINATION OPERATIONS

NASA-published estimates of four to six billion dollars.

The mission-driven program establishes stations in both low and high inclination orbits by 1992. It substantially exceeds the nominal NASA estimate.

Using the unified architecture and ignoring the high-inclination mission needs, a space station that serves the rapid onset of low-inclination missions can probably be acquired for less than six billion dollars.

If some of the cost saving potentials discussed on an earlier page could be realized, even the highest-cost mission-driven scenario could probably be afforded.

Program Strategy

The key points of our recommended program strategy are annotated in Table 21.

CONCLUSIONS OF THE STUDY

Our results indicate that a space station can provide scientific, economic, and social benefits. Further refinement of these results is needed, but we believe the need for permanent human presence in space is established, as noted in table 22.

The next year can be most profitably used by concentrating on how to achieve program objectives at the lowest practical life cycle cost. This involves architectural, technology, and programmatic considerations.

Actualizing the space station benefits is critically dependent on control of life cycle costs. Careful attention to system attributes that represent out-years cost drivers such as autonomy and maintainability is essential.

We are acutely aware of the debate over the

Table 21. Program Strategy

• Examine high-inclination mission requirements, costs, and benefits and select architectural options for necessary flexibility.
• Structure program so that commercial and foreign users pay their own way as early as possible, i.e., investment phase.
• Select technologies compatible with potential DoD applications.
• Emphasize life cycle cost in all decisions.
• Zero-base requirements and specifications selection.

Table 22. Concluding Remarks

• Role of man in space can be clarified, specified, and quantified.
• We have made a first detailed approximation.
• Space station benefits can be real.
• Practical, cost-effective architectures identified
• Definitive and comprehensive program planning required to actualize benefits.

benefits of permanent human presence in space. We believe we have established the reality of those benefits. We believe that the idea that "robotics is sufficient" does not take into account the importance and urgency of new initiatives in space science, technology, and industry—these require manned presence.

We are reminded of high government officials, in one case a president, who regarded the purchases of the Louisiana territory, and later of Alaska, as frivolous waste.

The development of permanent human presence in space will initiate the industrialization of Earth orbit. The U.S. must not abandon this goal to others.

No less than the survival of the United States as a major economic power is at stake.

APPENDIX 1

SUMMARY OF STUDY TASKS AND FINAL REPORT TOPICAL CROSS REFERENCE

SUMMARY OF STUDY TASKS

The study accomplished 3 major objectives:

1. Identified, collected, and analyzed science, applications, commercial, national security, technology development and space operations missions that require or benefit by the availability of a permanently manned space station. The space station attributes and characteristics that will be necessary to satisfy these requirements were identified.
2. Identified alternative space station architectural concepts that would satisfy the user mission requirements.
3. Performed programmatic analyses to define cost and schedule implications of the various architectural options.

Figure A-1 shows the summary task flow that was used to accomplish these objectives.

In Tasks 1.1 thru 1.5, missions were identified, screened, and their needs and benefits analyzed. Mission investigators were assigned to each of the mission classes (science and applications, commercial, technology development, space operations, and national security). In general, these investigators (and their supporting subcontractors) contacted potential users and analyzed available data to characterize potential mission needs. They worked in conjunction with designers and operations analysts to characterize the potential payloads and operational interfaces. In Task 1.6, the missions were allocated to orbits, and were assigned to platforms, free-flyers, or space stations, as appropriate. During Task 1.7, the various missions were integrated into time-phased mission models. The time-phasing took into account available budgetary constraints, prioritization, time sequencing constraints, and transportation availability. A computer program was used to process the integrated time-phased mission model to derive a year-by-year shuttle manifest schedule. The computer program was also used for Task 1.8 to derive the integrated time-phased space station accommodation requirements, i.e., power and thermal demands, berthing requirements, and crew skills. These mission analyses have been reported in Volume 2 of the final report.

Also included in Volume 2 are the results from Task 1.10. In this task, some of the primary commerical opportunities were examined to define the economics of the use of a space station and to define the benefits of doing business on a space station relative to doing it using the shuttle.

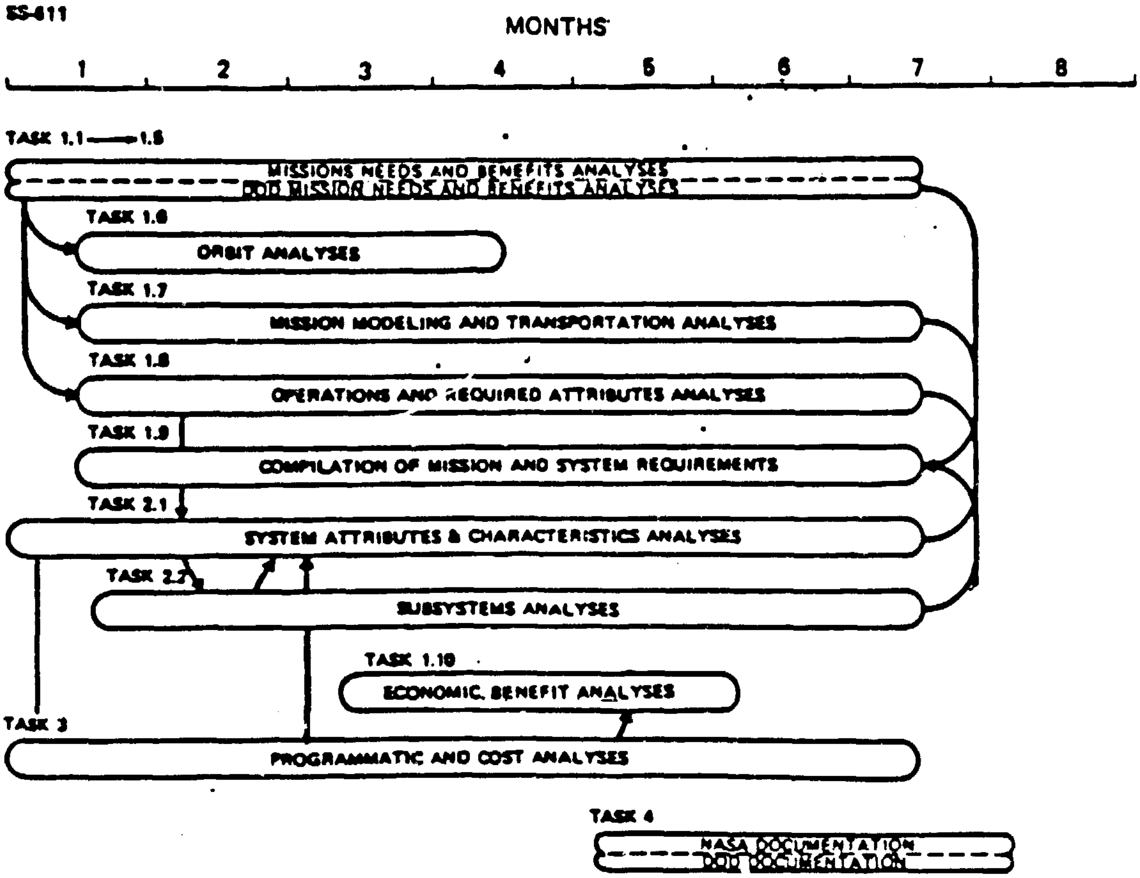

Figure A-1. Summary Diagram Outlines Major Task Traffic

In Task 1.9, mission requirements and space station design requirements were identified. An aggregate of these requirements are reported in Volume 3.

Volume 4 of the final report contains the results from Tasks 2.1, 2.2 and 3. Specifically in Task 2.1, a methodology for defining realistic architectural options was established. This methodology was applied using the requirements defined in the previous tasks. From this, we have created 3 architectural options and have shown some reference space station configuration concepts for each architectural option. Task 2.2 was performed to obtain analysis and trades of some of the principle subsystems, i.e., data management, environmental control and life support, and habitability. Task 3 provides the analyses of programmatics and cost options associated with the concepts derived during the study.

A cross reference guide to enable locating study topics within the volumes and volume sections of the final report is presented in Table A-1.

TABLE A-1

Final Report Topical Cross Reference Guide

Topic	Vol. 1 Exec Summ	Vol. 2 Mission Anal	Vol. 3 Rqm'ts	Vol. 4 Archit	Vol. 5 DoD	Vol. 6 Final Brief	Vol. 7-1 Sci/App Data Book	Vol. 7-2 Commer Data Book	Vol. 7-3 Tech Demo Data Book	Vol. 7-4 Archit Data Book	Vol. 7-5 Mission Data Book
Commercial Missions											
o Communication Satellites	o	3.2.1				o		o			
o Reconfigurable o Multibeam											
o Materials Proc.	o	3.2.2		I-1.3.2.3, 1.2.2.1		o		o			
o Semiconductors o Biological o Glass Fibers											
o Earth Observation		3.2.3									
Industrial Services		3.2.4						o			
o Crew Selection & Training o In-Space OPS											
Technology Demo's	o	3.3				o			o		
Space Operation	o	3.4				o					
o Construction o Flight Support o Servicing											

TABLE A-1

Final Report Topical Cross Reference Guide

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Science & Applications Missions											
o Space Environment Missions	o	3.1.2				o	o				
o Astrophysics Missions	o	3.1.3				o	o				
o Earth Environment Missions	o	3.1.4				o	o				
o Life Sciences Missions	o	3.1.5				o	o				
o Materials Science Missions	o	3.1.6					o				
Scenarios of Operational Capabilities o Mission Constrained o Station Constrained o No Space Station	o	4.0, 5.0				o					

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TABLE A-1

Final Report Topical Cross Reference Guide

Topic	Vol. 1 Exec Summ	Vol. 2 Mission Anal	Vol. 3 Rqm'ts	Vol. 4 Archit	Vol. 5 DoD	Vol. 6 Final Brief	Vol. 7-1 Sci/App Data Book	Vol. 7-2 Commer Data Book	Vol. 7-3 Tech Demo Data Book	Vol. 7-4 Archit Data Book	Vol. 7-5 Mission Data Book
Mission Requirements Summary		5.0									o
o Low Inclination Space Station	o	5.2,5.3	3.2.1	I-1.2.2.4		o					o
o High Inclination Space Station	o	5.2,5.3		I-1.2.2.4		o					o
o Platform only	o	5.4				o					o
o Manifesting o Shuttle o OTV o TMS	o	5.2, 5.3, 5.4				o					o
o Crew Size	o	5.2,5.3 5.4	3.2.1			o					o
o Crew Skills		5.2.5.3 3.1.2.5, 3.1.3.5, 3.1.4.5, 3.1.5.5, 3.2.1.5, 3.2.2.6, 3.2.3 3.3		II-2.2.3							o

TABLE A-1

Final Report Topical Cross Reference Guide

Topic	Vol. 1 Exec Summ	Vol. 2 Mission Anal	Vol. 3 Rqm'ts	Vol. 4 Archit	Vol. 5 DoD	Vol. 6 Final Brief	Vol. 7-1 Sci/App Data Book	Vol. 7-2 Commer Data Book	Vol. 7-3 Tech Demo Data Book	Vol. 7-4 Archit Data Book	Vol. 7-5 Mission Data Book
Mission Requirements Summary (Continued)											
o Accommodations Reqm'ts	o	2.2 5.2, 5.3	3.2.1			o					o
o Power		5.4	1-1.2.1.2, 1.2.2.4 1.2.3.3 1.2.3.4								
o Internal Vol											
o Berthing Ports											
Benefits		6.0									
o Semiconductor Manufacturing	o	6.2				o					o
o Glass Fiber Manufacturing	o	6.3				o					o
o Communications Satellite Assembly	o	6.4				o					o
o Biological Materials Manufacturing	o	6.5				o					o

TABLE A-1

Final Report Topical Cross Reference Guide

Topic	Vol. 1 Exec Summ	Vol. 2 Mission Anal	Vol. 3 Rqm'ts	Vol. 4 Archit	Vol. 5 DoD	Vol. 6 Final Brief	Vol. 7-1 Sci/App Data Book	Vol. 7-2 Commer Data Book	Vol. 7-3 Tech Demo Data Book	Vol. 7-4 Archit Data Book	Vol. 7-5 Mission Data Book
Mission Analysis											
o Manifesting Analysis Software	o	2.2				o					o
o Accommodations & Crew Activity Analysis Software o Crew Skills o Crew Size o Berthing Ports o Electrical power o Internal volume	o	2.2				o					o
Design Requirements											
o Mission Accommodation Reqm'ts		5.0	3.2								
o Interfaces o Berthing/Docking Port				iI-10.0 I-1.3.2.1						o	
o Hangar		3.3		I-1.3.2.2							

TABLE A-1

Final Report Topical Cross Reference Guide

Topic	Vol. 1 Exec Summ	Vol. 2 Mission Anal	Vol. 3 Rqm'ts	Vol. 4 Archit	Vol. 5 DoD	Vol. 6 Final Brief	Vol. 7-1 Sci/App Data Book	Vol. 7-2 Commer Data Book	Vol. 7-3 Tech Demo Data Book	Vol. 7-4 Archit Data Book	Vol. 7-5 Mission Data Book
Architectural Options											
o Architecture Development Methodology	o			I-1.1		o				o	
o Space Station Architectural Options	o			I-1.2		o				o	
Build-up and Growth	o	5.0		I-1.2.3.4, 1.3.1.3, 1.3.2.3, 1.3.3.3							
Data Management											
o Architecture				II-3.2						o	
o In-Flt Checkout				II-3.3						o	
o Space-Ground Integration				II-3.4						o	
o Ground Lab				II-3.5						o	
o Software Devel.				II-3.6						o	
o Hardware Stds				II-3.7						o	
o Software Stds				II-3.8						o	
o Verif/Valid.				II-3.9						o	

TABLE A-1

Final Report Topical Cross Reference Guide

Topic	Vol. 1 Exec Summ	Vol. 2 Mission Anal	Vol. 3 Rqm'ts	Vol. 4 Archit	Vol. 5 DoD	Vol. 6 Final Brief	Vol. 7-1 Sci/App Data Book	Vol. 7-2 Commer Data Book	Vol. 7-3 Tech Demo Data Book	Vol. 7-4 Archit Data Book	Vol. 7-5 Mission Data Book
Logistics/Resupply											
o Logistics Module				II-7.1, 7.3,7.4							
o Resupply Reqm'ts				II-7.2							
Environmental Control and Life Support Subsystem				II-5.0						o	
o ECLS Evolution				II-5.2.1, 5.3.2						o	
o Safe Haven Logistics Module				II-5.2.1						o	
o Air Revitalization System				II-5.0,5.3.2						o	
o Water Revitalization System				II-5.0,5.3.2						o	
o Performance and Loads Specification										o	
o Overboard Venting				II-5.2.1,5.2.2						o	
o Architecture				II-5.2.1						o	
o Water Recovery System				II-5.0,5.3.2						o	
o CO_2 Concentration				II-5.0,5.3.2						o	
o Regenerative-Fuel-Cell-Based ECLS				II-5.0,5.2.1, 5.3.2						o	
o Recommendations				II-5.0, 5.3.2						o	
EVA/EMU				II-5.0, 5.2.2						o	

TABLE A-1

Final Report Topical Cross Reference Guide

Topic	Vol. 1 Exec Summ	Vol. 2 Mission Anal	Vol. 3 Rqm'ts	Vol. 4 Archit.	Vol. 5 DoD	Vol. 6 Final Brief	Vol. 7-1 Sci/App Data Book	Vol. 7-2 Commer Data Book	Vol. 7-3 Tech Demo Data Book	Vol. 7-4 Archit Data Book	Vol. 7-5 Mission Data Book
Communications & Tracking Subsystem			3.2.2.1.11	II-4.0						o	
Manipulator System				II-6.0						o	
Pointing Systems				II-8.0						o	
Thermal Management				II-9.0						o	
Crew				II-2.0							
o Tasks				II-2.2						o	
o Skills		5.2.5.3 3.1.2.5, 3.1.3.5, 3.1.4.5, 3.1.5.5, 3.2.1.5 3.2.2.6, 3.2.3 3.3		II-2.2.3							
o Capabilities				II-2.2.2						o	
o Role Relationships				II-2.3.2						o	
o Accommodations			3.2.2.1.11	II-2.4						o	

TABLE A-1

Final Report Topical Cross Reference Guide

Topic	Vol. 1 Exec Summ	Vol. 2 Mission Anal	Vol. 3 Rqm'ts	Vol. 4 Archit	Vol. 5 DoD	Vol. 6 Final Brief	Vol. 7-1 Sci/App Data Book	Vol. 7-2 Commer Data Book	Vol. 7-3 Tech Demo Data Book	Vol. 7-4 Archit Data Book	Vol. 7-5 Mission Data Book
Crew (Continued)											
o Habitability	o		3.2.2.1.11	II-2.0,2.4						o	
o IVA Work Stations				II-2.5.2						o	
o EVA Work Stations				II-2.5.3 II-5.[illegible].2						o	
o Maintenance				II-2.5.4						o	
o Stowage			3.2.2.1.11							o	
o Windows			3.2.2.1.11	II-2.4.1						o	
o Hygiene			3.2.2.1.11	II-2.4.2.4						o	
o Scheduling			3.2.2.1.11	II-2.3.1						o	

APPENDIX 2

KEY TEAM MEMBERS

KEY TEAM MEMBERS

Subject	Boeing Team	Subcontractor Team	
Study Manager	Gordon Woodcock	ADL:	Dr. Peter Glaser
		Battelle:	Kenneth E. Hughes
		ECON:	John Skratt
		ERIM:	Albert Sellman
		Hamilton Standard:	Harlan Brose
		Intermetrics:	John Hanaway
		Life Systems:	Franz Shubert
		MRA:	Col. Richard Randolph (Ret.)
		NBS:	Dr. B. J. Bluth
		RCA:	Dr. Herbert Gurk
		SAI:	Dr. Hugh R. Anderson
Technology Manager	Dr. Richard L. Olson		
Mission Analysis			
Science & Applications	Dr. Harold Liemohn	SAI:	Dr. Hugh R. Anderson (Environmental Science)
	David Tingey (Earth Obs.)		
	Dr. Derek Mahaffey (Mission Integration)		Dr. Peter Hendricks (Meterology/ Oceanography)
	Melvin W. Oleson (Life Sciences)		Dr. Gil Stegen
	Dr. Robert Spiger (Plasma physics, astro-physics, solar physics)		Dr. John Wilson (Life Sciences)
			Dr. Robert Loveless (Integration)
			Dr. Robin Muench
			Dr. Stuart Gorney (Life Sciences)
			Ms. Monica Dussman (Life Sciences)
		ERIM:	Albert Sellman (Earth Obs.)
			Dr. Irvin Sattinger (Earth Obs.)
Commercial	Dr. Harvey Willenberg	RCA:	Dr. Herbert Gurk
			Thaddeus (Ted) Hawkes
		ADL:	Dr. Peter Glaser
		Battelle:	Dr. Kenneth E. Hughes
		MRA:	Col. Richard Randolph (Ret.)
			Robert Pace

KEY TEAM MEMBERS (Cont'd)

Subject	Boeing Team	Subcontractor Team	
Mission Analysis (Cont'd)			
Technology Demonstrations	George Reid Dr. Alan G. Osgood David S. Parkman Steve Robinson Richard Gates Tim Vinopal		
National Defense	Robert S.Y. Yoseph	ERIM:	Mirko Najman
Space Operations	Keith H. Miller		
Architecture and Subsystems			
Architecture & Configurations	John J. Olson Brand Griffin Tim Vinopal David S. Parkman Steve Robinson		
Communications		RCA:	Donald McGiffney
Crew Systems	Keith H. Miller George Reid Dr. Alan G. Osgood	NBS:	Dr. B. J. Bluth
Data Management and Software	Les Holgerson	Intermetrics:	John Hanaway
ECLSS	Keith H. Miller	Ham Std:	Harlan Brose Ross Cushman Al Boehm Ken King Todd Lewis
		Life Systems:	Dr. R. A. Winveen Franz Schubert Dr. Dennis B. Heppner
Operations Analysis	Keith H. Miller George Reid Dr. Alan G. Osgood		
Orbit Analysis	Dani Eder		

KEY TEAM MEMBERS (Cont'd)

Subject	Boeing Team	Subcontractor Team	
Architecture and Subsystems (Cont'd)			
Orbit/Survivability Analysis	Stephen W. Paris Merri Anne Stowe		
C^3I	H. Paul Janes		
Radiation Effects	Dr. William C. Bowman		
Requirements Analysis	Lowell Wiley		
Programmatics & Cost			
Cost Analysis	Ken verGowe	ECON:	Ed Dupnick
Programmatics	Gordon Woodcock		

APPENDIX 3

ACRONYMS AND ABBREVIATIONS

LIST OF ACRONYMS AND ABBREVIATIONS

AAP	Airlock Adapter Plate
AC	Alternating Current
ADM	Adaptive Delta Modulation
AM	Airlock Module
APC	Adaptive Predictive Coders
APSM	Automated Power Systems Management
ACS	Attitude Control System
ARS	Air Revitalization System
ASE	Airborn Support Equipment
BIT	Built in Test
BITE	Built in Test Equipment
CAMS	Continuous Atmosphere Monitoring System
C&D	Controls and Displays
C&W	Caution and Warning
CCA	Communications Carrier Assembly
CCC	Contaminant Control Cartridge
CCTV	Closed Circuit Television
CEI	Critical End Item
CER	Cost Estimating Relationship
CF	Construction Facility
CMG	Control Moment Gyro
CMD	Command
CMDS	Commands
CO_2	Carbon Dioxide
CPU	Computer Processor Units
CRT	Cathode Ray Tube
dB	Decibels
DC	Direct Current
DCM	Display and Control Module
DDT&E	Design, Development, Test, and Evaluation
DOD, DoD	Department of Defense
DT	Docking Tunnel
DM	Docking Module
DMS	Data Management System
DSCS	Defense Satellite Communications System
ECLSS	Environmental Control/Life Support System
EDC	Electrochemical Depolarized CO_2 Concentrator
EEH	EMU Electrical Harness
EIRP	Effective Isotropic Radiated Power
EMI	Electromagnetic Interference
EMU	Extravehicular Mobility Unit
EPS	Electrical Power System
ET	External Tank
EVA	Extravehicular Activity
EVC	EVA Communications System
EVVA	EVA Visor Assembly
FM	Flow Meter
FMEA	Failure Mode and Effects Analysis
ftc	Foot candles
FSF	Flight Support Facility
FSS	Fluid Storage System
GaAs	Gallium Acsenide

LIST OF ACRONYMS AND ABBREVIATIONS (Continued)

GN&C	Guidance, Navigation and Control
GEO	Geosynchronous Earth Orbit
GHZ	Gigahertz
GPC	General Payload Computer
GPS	Global Positioning System
GSE	Ground Support Equipment
GSTDN	Ground Satellite Tracking and Data Network
GFE	Government Furnished Equipment
GTV	Ground Test Vehicle
HLL	High Level Language
HLLV	Heavy Lift Launch Vehicle
HM	Habitat Module
HMF	Health Maintenance Facility
HPA	Handling and Positioning Aide
HUT	Hard Upper Torso
Hz	Hertz (cycles per second)
ICD	Interface Control Document
IDB	Insert Drink Bag
IOC	Initial Operating Capability
IR	Infrared
IVA	Intravehicular Activity
JSC	Johnson Space Center
KBPS	Kilo Bits Per Second
KM, Km	Kilometers
KSC	Kennedy Space Center
lbm	Pounds Mass
LCD	Liquid Crystal Display
LCVG	Liquid Cooling and Ventilation Garment
LED	Light Emitting Diode
LEO	Low Earth Orbit
LiOH	Lithium Hydroxide
LM	Logistics Module
LPC	Linear Predictive Coders
LRU	Lowest Replaceable Unit
LSS	Life Support System
LTA	Lower Torso Assembly
LV	Launch Vehicle
lx	Lumens
MBA	Multibeam Antenna
mbps	Megabits per second
MHz	Megahertz
MMU	Manned Maneuvering Unit
MM-Wave	Millimeter wave
MOTV	Manned Orbit Transfer Vehicle
MRWS	Manned Remote Work Station
MSFN	Manned Space Flight Network
N/A	Not Applicable
NBS	National Bureau of Standards
NSA	National Security Agency
N	Newton
NiCd	Nickel Cadmium
NiH_2	Nickle Hydrogen

LIST OF ACRONYMS AND ABBREVIATIONS (Continued)

Nm,nm	Nautical miles
N/m^2	Newtons per meter squared
OBS	Operational Bioinstrumentation System
OCS	Onboard Checkout System
OCP	Open Cherrypicker
OMS	Orbital Manuevering System
OTV	Orbital Transfer Vehicle
PCM	Pulse Code Modulation
PCM	Parametric Cost Model
PEP	Power Extension Package
PIDA	Payload Installation and Deployment Apparatus
P/L	Payload
PLSS	Portable Life Support System
PM	Power Module
POM	Proximity Operations Module
ppm	Parts per Million
PRS	Personnel Rescue System
PSID	Pounds per Square Inch Differential
RCS	Reaction Control System
REM	Roentgen Equivalent Man
RF	Radio Frequency
RFI	Radio Frequency Interference
RMS	Remote Manipulator System
RPM	Revolutions Per Minute
RPS	Real-time Photogrammetric System
SAF	Systems Assembly Facility
SAWD	Solid Amine Water Desorbed
SPGaAs	Space Produced Gallium Arsenide
scfm	Standard Cubic Feet per Minute
SCS	Stability and Control System
SCU	Service and Cooling Umbilical
SDV	Shuttle - Derived Vehicle
SDHLV	Shuttle - Derived Heavy Lift Vehicle
SEPS	Solar Electric Propulsion System
SF	Storage Facility
SM	Service Module
SOC	Space Operations Center
SOP	Secondary Oxygen Pack
SRB	Solid Rocket Booster
SRMS	Shuttle Remote Manipulative System
SRU	Shop Replacable Units
SSA	Space Suite Assembly
SSME	Space Shuttle Main Engine
STS	Space Transportation System
SSP	Space Station Prototype
STAR	Shuttle Turnaround Analysis Report
STDN	Spaceflight Tracking and Data Network
STE	Standard Test Equipment
TBD	To Be Determined
TDRSS	Tracing and Data Relay Satellite System
TFU	Theoretical First Unit
TGA	Trace Gas Analyzer

LIST OF ACRONYMS AND ABBREVIATIONS (Continued)

TIMES	Thermoelectric Integrated Membrane Evaporation System
TLM	Telemetry
TM	Telemetry
TMS	Teleoperator Maneuvering System
TT	Turntable/Tilttable
TV	Television
UCD	Urine Collection Device
VCD	Vapor Compression Distillation
VDC	Volts Direct Current
VLSI	Very Large Sacle Integrated Circuits
VSS	Versatile Servicing Stage
WBS	Work Breakdown Structure
WMS	Waste Management System